DEPARTMENT OF DEFENSE

MILITARILY CRITICAL TECHNOLOGIES

PART III: DEVELOPING CRITICAL TECHNOLOGIES

SECTION 11: LASERS AND OPTICS TECHNOLOGY

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SECTION 11—LASERS AND OPTICS TECHNOLOGY

Scope

Highlights

- Lasers (coherent radiation) permit observation of the structures and dynamics of molecules, crystals, and proteins. This technology is predicted to become a revolutionary tool for better understanding molecular physics, particularly in the field of medicine.
- Microreplication and fabrication of microelectronic components using lasers will be significantly improved by means of shorter exposure times, higher intensity excellent collimation, and better resolution available with newly developed laser technology.
- Rapid advances in laser diode bar and array manufacturing are now pacing solid-state laser development for DoD mid-infrared (IR) countermeasures (CM), remote battlefield sensing, illumination, and laser range finder (LRF)/designators and laser weapons.
- Short-wavelength coherent laser radiation may permit observation of the structures and dynamics of molecules, crystals, and proteins in vivo.
- The battlefield efficiency of modern (platforms) armor, aircraft, missiles, and infantry will be greatly increased through the use of new lasers, along with the use of sophisticated detection and imaging systems for target acquisition, tracking, fire-control systems, and remote communications.
- The deeper penetration of the high-energy photons (X-ray, γ-ray lasers) in a target overcomes the counter-measures designed against beams that deposit energy on the surface such as long-wavelength lasers.
- Nanotechnology will result in significant improvement in electro-optic and nonlinear optic devices, which will have widespread military applications.
- Micro-optics will begin complementing and then replacing electronic components on chips, reducing heat and improving speed and throughput while reducing cost.
- Continued advances in optical coating material technologies will result in improved hardness capability of various military optics hardware.
- Lightweight technology for space optics, vital to our space requirements, will be addressed by numerous new technology applications of high-strength composites.
- Integrated design, fabrication, test, and assembly methods will permit the transition of today’s hybrid optical devices into the fully integrated optical systems required for miniaturization and high performance in future products.
- Real-time, computer-controlled optical grinding and polishing, along with micropolishing, will cut the time required to fabricate aspheric optics by a factor of 10 or more.

Highlights (continued)

- Integrated design, fabrication, test, and assembly methods will permit the transition of today's hybrid optical devices into the fully integrated optical systems required for miniaturization and high performance.
- Multispectral sensors are an enabling technology for the commercial sector as well as the military.
- High-sensitivity night vision (NV) optical sensors and improved coatings will greatly improve current NV capabilities.

OVERVIEW

This section covers militarily critical technologies being developed for lasers, optics, optical materials, optoelectronics, and photonics, as well as specific supporting technologies and applications. The primary goal in this section is to identify and list technologies and materials that could conceivably result in

- major improvements in currently available as well as developmental military laser/optics systems and components;
- the development of significantly new cost-saving approaches to the generation of both low- and high-power coherent radiation sources;
- the development of high-efficiency, lightweight optical components and systems;
- the development of information technology and telecommunication optics/laser components;
- the improvement of adaptive-optics compensation;
- the development of micro and nano-technology as they pertain to optics and lasers; and
- the expansion of the range of operability of lasers to shorter wavelengths (including X-rays and the γ-ray regime).

High-energy laser (HEL) and low-energy laser (LEL) systems are covered in this section. High-power lasers (HPL) used in Directed-Energy Systems are covered in Section 6 of MCT Part III. The HEL/LEL cutoff is at 20 kW of power CW and 1 kJ of energy per pulse. HEL lasers are designated as those that produce a continuous wave (CW) or repetitive pulsed-average power level in excess of 20 kW.

Technologies applicable to the development and production of lasers and laser systems in the infrared (IR), visible and ultraviolet (UV) regions of the electromagnetic (EM) spectrum (0.01 µm to 30 µm) capable of achieving militarily significant levels of energy or power are covered in this section. In addition, short-wavelength lasers based on electronic transitions, X-ray lasers (0.01 µm and shorter wavelengths), and γ-ray lasers based on nuclear transitions (10^{-4} to 10^{-6} µm and shorter) are covered in this section. Although γ-ray lasers have not been developed yet, work on technologies that could provide the basis for these lasers is ongoing and covered in this section. Lasers consist of the laser hardware (the device) and the laser medium (or host material). Lasers may operate in a continuous, repetitive, repetitive burst, or single-pulsed mode, depending on the application and requirements. Laser systems incorporate components such as amplifier stages, frequency conversion components, Raman cells, multiple-wave mixing components, or other major elements, in addition to the laser oscillator. Reliability of laser diode bars operated in high-density/high-power arrays is critical to most solid-state laser applications.

The optics covered in this section include all optics, optical components, and optical materials being developed for future optical, laser, or combination laser-optics systems that appear to have significant military system applications. The optics covered in this section include elements designed to operate in the same wavelength range as that of the lasers, 30 µm to 10^{-6} µm.

Critical optical technologies encompass optical materials; optical filters; fiber optics; nonlinear optical (NLO) components; and optics for LEL, HPL, and HEL military applications on land, sea, air, and in space. The primary use of nonlinear optics is for wavelength conversion and optical on-chip switching, as well as beam-phase conjugation and image-enhancement applications, including shared aperture technologies for both directed-energy weapons (DEW) and HEL weapons (DEW/HEL). NLO are also used in pointing and tracking applications, as well as missile guidance systems. Cooled-laser optics for both active- and passive-cooling applications are also covered.

Laser brightness and beam collimation contribute to greater range capability. Laser tunability and wavelength diversity are critical for optical counter and counter-countermeasures. Micro-optical devices are envisioned to replace some chip electronics with significant cost reductions while providing higher efficiency and reliability. Optical storage of information is envisioned to replace current magnetic computer memory. Optical advances are also being developed for national defense in surveillance, night vision, laser systems, fiber optics, displays, and special countermeasure applications. A prime application for the military is in the weapons field, for search, track, and guidance systems, as well as laser weapons. The developing technologies for HEL systems are covered in the DEW section of Part III; however, the new developing laser technologies, which may be applicable to those weapons, are outlined in this section.

This section outlines developing technologies in all applications of lasers and optics used for military applications, including weapons, missile guidance, rangefinding, optical information processing, telecommunications, storage and transport, optical filters, optical displays, sensing, and illumination, as well as associated technologies in optical and laser components and materials being developed for future military applications. These lasers, optics, and associated power systems are listed in their appropriate subsections as independent items.

RATIONALE

The method of fighting wars is changing. Optics and lasers are constantly encountered in military systems, from low-cost components to complex and expensive systems, and have dramatically changed the way wars are fought. Sophisticated satellite surveillance systems are a keystone of intelligence gathering. Night vision imagers and missile guidance units are allowing our armed forces to “own the night.” Lasers are used for many applications—from targeting and range finding to navigation—and may lead to high-power DEWs. Reconnaissance warfare is based on real-time, all-weather, accurate and secure information systems combined with long-range, unmanned, smart, highly lethal weapons designed to achieve pinpoint precision kills. Optics and laser technologies enable us to reduce dramatically our response time as political and military events warrant.

Lasers are used in many military applications. HPLs, such as those with lethal energy for missile applications, include CO_2 lasers, as well as chemical lasers and chemical transport lasers such as oxygen-iodine lasers. The principal applications of critical military systems that employ long-wavelength lasers, however, are those that seek to facilitate the conduct of military operations at night or under conditions of limited visibility and those used for guided munitions. The critical military applications include the following:

- ranging—for artillery systems, helicopters, and armored vehicles;
- target designation—day/night;
- semi-active guidance—for laser-guided weapons;
- imaging—for target acquisition.

Lasers currently employed on the battlefield, as well in air and naval military systems, mainly use neodymium: yttrium/aluminum garnet (Nd:YAG)-based lasers. These operate in the near-visible region (approximately 1,000 nm). They can be easily detected by most night-vision systems, but they are capable of sensor blinding as well as eye blinding. Consequently, a new family of “eye safe” lasers has been introduced for a number of applications (e.g., range finders, target illuminators). These operate between 1,400 and 2,000 nm, in the eye safe regime.

Long-wavelength lasers are a vital part of modern battlefield systems. They are currently incorporated as part of guided ordnance such as laser-guided bombs. LELs have found utility on the battlefield for covert communications, ranging, and aim-point selection, and have the capability to blind personnel. They are used as illuminators in conjunction with low-light imaging systems. LELs with a wavelength between 1.3 and 1.55 µm have applications in very long distance fiber-optic communications, providing links for command and control. Moderate power lasers are used for in-band sensor blinding to negate optically augmented ordnance. HELs and HPLs are being developed as long-range lethal weapons for target destruction or mission abortion. [The principal military applications for short-wavelength lasers are space-based DEWs and high-resolution fabrication and material processing techniques (see Section 6).]

In less than 40 years, the laser has grown from a laboratory demonstration to a standard industrial, medical, and military usage. Early on, it was evident that lasers required special optics—optics that had very low absorption and high reflectivity. Today, the applications for lasers cover a vast horizon, from information technology, profile and distance measuring, and telecommunications; to welding, cutting, and heat treatment; to illuminators and scanners; to medicine, surgery, and health care applications; as well as specific applications for national defense. The application of optics has grown significantly as well. Lasers need optics to function, and as a result, the expansion of optics technology in both the purest sense as well as in the manufacturing phase has grown exponentially. The Desert Storm conflict pointed out the military's need for and advantage of lasers and optics with laser-guided bombs and night-vision optical sights, both of which provided a significant advantage for the allies.

Optics has grown in military importance "hand-in-hand" with laser technology. According to a National Research Council (NRC) report:

> Throughout history, new technology has had a profound effect on how wars are conducted. Usually, the victors were those best able to apply the new technology. Over the course of the past 50 years, nuclear weapons, microwave radar, guided missiles, and other developments have led to major realignments of defense strategy. Today, the traditional modern strategy of massing large numbers of military personnel and materiel to engage enemy forces is giving way to high-tech methods of conducting warfare that minimize casualties. The U.S. military mission now requires a versatile fighting force capable of both conventional field and urban warfare in a global venue. To improve the effectiveness of the combatant while reducing casualty rates, the military has a number of efforts under way that include reliance on speed and stealth to overcome opposing forces; a better equipped land warrior; rapid detection and control of nuclear, chemical, and biological threats; and dissemination of real-time intelligence on enemy targets. Optics plays a key enabling role in these plans. For the future, optical systems are sure to be the basis for entirely new classes of defense applications that will change yet again the way wars are conducted.[1]

BACKGROUND

Lasers and optics constitute a diverse body of technologies. Since the discovery of lasers in the late 1950's, there has been an exponential growth of laser and laser-related technology. The U.S. military led the charge in laser development during the 1960's and 1970's in the various government laboratories. Over the years, industry has found many commercial applications that justify corporate funding, resulting in broad-based industry involvement today.

The development of the ruby laser in 1960 provided resurgence to optics and the field of lasers and electro-optics. The optics technologies described in this section are being developed to improve efficiency, provide longer life expectancy, reduce costs, and replace outdated technology in other application sectors such as electronics. Optical communications and optical memory storage are just two areas in which optics are rapidly replacing electronic components.

Lasers and optics have become a key part of everyday life—they are found in the scanner at the grocery checkout counter and in compact disc (CD) players. Lasers and optics have solved many requirements for military applications; new, advanced technologies are anticipated to make significant improvements in the future. Early laser research workers had visions of firing lasers at missiles and destroying other targets with a "speed-of-light" weapon. It has taken many years (some 30) to demonstrate such a capability. Although airborne and space lasers are now on the drawing boards, they have many limitations because of materials and manufacturing process issues.

A new area of research in which optics and lasers are playing a vital role is microelectromechanical systems (MEMS). MEMS technology may have a profound effect on the military and civilian sectors. For example, MEMS devices might be used in microsatellites having a total mass less than 1 kg for battlefield surveillance. In addition, MEMS devices with motors and repositioning mirrors have been constructed for use with "on-chip technology."

Optics and laser technologies have matured in the specialized telecommunications information technology arenas and in three-dimensional image storage devices. Optics and electro-optics research technologies are now the predominant emerging technologies in the laser optics field.

Many new technologies are being developed that will address one or more military applications. Some of the key issues identified in the NRC report include the following:

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[1] NRC, "Harnessing Light: Optical Science and Engineering for the 21st Century," 1998.

- High efficiency, lower manufacturing cost, laser diode arrays.
- Diode array pumped solid-state lasers for lightweight, high-efficiency laser range finders (LRFs).
- Eye-safe solid-state lasers for "friendly" near-range battlefield issues.

The laser weapon concept has been demonstrated both on the ground and in airborne configurations; however, there are numerous technical challenges left that must be solved. At first glance, HPLs would seem to serve only military needs; however, advances in these technologies have provided many other uses for scientific and commercial applications. The NRC report lists the following technical challenges in the HPL area:

- Stabilizing optical resonators under high thermal loading conditions.
- Producing high optical quality, near diffraction limited beams with high efficiency.
- Improving propagation by suppressing nonlinear optical effects along the propagation path.
- Improving adaptive optics to correct for beam distortions during propagation.
- Solving operational issues such as environmental factors and lethality for different target classes.

TECHNOLOGY ASSESSMENT

Optics is a pervasive enabling technology. Lasers require optics in every facet of the laser system. Not surprisingly then, optics and lasers are rapidly becoming an important focus for new business in the global economy. In the United States, both large and small businesses are significant players in emerging optics and laser technology.

Optics and lasers are used in many military and commercial applications. Lasers are finding more "homes" everyday in military systems, from weapons applications to ranging to information transmission and communications. As the impact of optics and lasers has increased, changes have become necessary in the design, manufacturing, and process controls of these new technologies to provide affordable systems. One example is the emergence of a new class of computer-controlled optical grinding and polishing machines that reduced the time necessary to complete the fabrication of an aspheric lens element to less than 1/10 that of conventional methods and with a higher degree of figure control.

The use of commercial optical and laser items and technologies is important in the overall affordability of a military component or system; however, many commercially available optics and laser products require special parameters or special adaptations to meet military needs. For example, displays in the military environment must work in high ambient light levels, and many optical and laser devices must withstand high ambient temperatures. These special DoD operational requirements, combined with the need for only limited quantities, dictates the need for continued DoD support of these research and manufacturing technologies. To summarize a number of recent reports, including the NRC report, a coordinated multiyear DoD plan needs to be implemented and followed. This plan should cover development of the specialized technologies required to improve performance and reduce cost for optical and laser systems and development of an RF photonic phased antenna-array technology for radar and communications. In addition, key technologies such as HPL activities and new optics and optical technologies should continue to be pursued by DoD to improve affordability and efficiency of U.S. military systems, while providing a clear technological advantage in the next generation of weapons.

Optical microtechnology and nanotechnology, combined with information technology and biotechnology, will enable real-time, noninvasive monitoring of the health status of military or civilian personnel. The chip-level integration of optics, lasers, and electronics will lead to wearable devices capable of real-time sensing of body fluids, the on-chip processing of the sensed information, and the transmission of the processed results to medical facilities.

Technology has driven each military era's definition of precision. In the 21st century, it will be possible to find, fix, or track and target anything that moves on the surface of Earth using lasers and optics. This emerging reality will change the conduct of warfare and the role of air, land, sea, and space power.

WORLDWIDE TECHNOLOGY ASSESSMENT

Many industrialized nations have the technological know-how to produce specialized lasers and optics for use in both military weapon and non-weapon roles. Several smaller countries are making inroads into the laser rangefinder market, cutting the U.S. and Russian share. The United States and Russia have the broadest overall capability in lasers. Whereas the UK, France, Germany, and Japan have specialized capability in selected types of commercial and military lasers and optics, at least 75 percent of the militarized countries in the world today have deployed some non-weapon lasers. Most of these systems use Nd:YAG lasers at 1,064 nm. (This wavelength can damage the unprotected eye.) The number of nations with a capability to produce the newer eye safe lasers (wavelengths greater than 1,200 nm) is still limited because of limited dual-use applications.

It is clear that defense against ballistic and cruise missiles is an increasingly important element of U.S. national security. The rapidly growing theater and global threat posed to the United States and U.S. interests by cruise and ballistic missiles of Third World countries is accelerating the national interest in developing a defense architecture to counter this threat. Optical surveillance and guidance systems, partnered with high-power lasers, are believed to be effective for theater and ballistic missile defense. New and developing technologies in the laser and optics disciplines are increasing at an exponential rate worldwide. Many of our allies, as well as our adversaries, have the capability to develop advanced optics and laser technologies for military applications. Many are pursuing one or more key technologies that are of utmost importance to our military. As a result, this technology assessment will include any known developing technology that the international community is pursuing.

Country	Sec. 11.1 Lasers	Sec. 11.2 Optics	Sec. 11.3 Optical Materials and Processes	Sec. 11.4 Supporting Technologies and Applications	Sec. 11.5 Optoelectronics and Photonics Technology
Australia	●	●		●	●
Canada	●●●	●	●		
China	●●●	●●	●●●	●●●	●●●
France	●●●	●	●●	●●●	●●●
Germany	●●●	●●	●	●●	●●
India				●	●
Israel	●●	●	●	●	●
Italy	●●	●			
Japan	●●●	●●	●●●	●●●	●●●
Malaysia			●		
Netherlands	●		●	●	●
Norway	●	●	●	●	●
Russia	●●●	●●	●		
Singapore		●	●●	●	●
South Korea	●	●	●●	●●●	●●●
Sweden		●	●	●	●
Switzerland		●	●	●	●
Taiwan		●	●●		
Ukraine	●	●	●		
UK	●●●	●	●●	●●	●●
United States	●●●●	●●●	●●●	●●●●	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Figure 11.0-1. Lasers and Optics Systems WTA Summary

SECTION 11.1—LASERS

Highlights

- Microchip lasers and photonic crystal lasers in NLO media will revolutionize the current electronic chip industry.
- Laser-coherent radiation permits observation of the detailed structures and dynamics of molecules, crystals, and proteins.
- Microreplication and fabrication of microelectronic components using short-wavelength lasers will be improved with shorter exposure times, higher intensity excellent collimation, and better resolution.
- In spectroscopy, with shorter wavelength lasers, higher energy resolution will permit greater discrimination, while deeper penetration will permit inspection of thicker samples.
- Solid-state lasers have a much higher volume density of ions, permitting construction of the smallest and most portable systems when pumped with laser diode bars/arrays.
- Short-wavelength coherent radiation may permit observation of the structures and dynamics of molecules, crystals, and proteins in vivo.
- The battlefield efficiency of modern (platforms) armor, aircraft, missiles, and infantry has been greatly increased through the use of lasers, along with the use of sophisticated detection and imaging systems for target acquisition, tracking, and fire-control systems.
- Propagation through the atmosphere is a major issue because of attenuation and scattering, but judicious selection of the laser wavelength and pulse mode along with active atmospheric compensation can alleviate the problem and restore required energy delivery on target.
- Because the beam travels at the speed of light, tracking problems associated with slower beams (particle beams) are avoided.
- The deeper penetration of the high-energy photons (X-ray, γ-ray lasers) in a target overcomes the countermeasures designed against beams that deposit energy on the surface like long-wavelength lasers.
- An X-ray (γ-ray) laser weapon is nominally considered only for space applications, to be used against missiles and satellites.
- Laser tracking permits more accurate and faster determination of target position.
- High-power laser weapons can be used in strategic and tactical scenarios.
- A γ-ray laser beam (graser) could penetrate deeply into a target and would be capable of producing a range of lethal mechanisms from soft kill to hard kill.

OVERVIEW

This section identifies developing laser technologies that could conceivably have a significant impact on future DoD systems. Laser developments include the following: (a) major improvements in currently available lasers; (b) the development of significantly new cost-saving design, fabrication, and logistic support technologies for the generation of both low- and high-power coherent radiation sources; and (c) the expansion of the laser operability range to shorter wavelengths (including X-rays and the γ-ray regime) and smaller dimensions (including micro- and nano-chip level lasers). Lasers may operate in a continuous, repetitive-pulse, repetitive-burst, or single-pulsed mode, depending on the application and requirements. Laser systems sometimes incorporate components such as amplifier stages, frequency conversion components, optically pumped semiconductors, Raman cells, and multiple-wave mixing components or other major elements, in addition to the laser oscillator. Both HEL and LEL systems are covered in this section. HELs are lasers that produce a CW power level in excess of 20 kW or pulsed lasers.

Technologies applicable to the development and production of lasers and laser systems in the IR, visible, and UV regions of the EM spectrum from 0.01 μm to 30 μm will be outlined. In addition, short-wavelength lasers based on electronic transitions, X-ray lasers (0.01 μm and shorter wavelengths), and γ-ray lasers, based on nuclear transitions (10^{-4} to 10^{-6} μm and shorter) are covered in this section. Although γ-ray lasers have not been developed yet, work on technologies that could provide the basis for these lasers is ongoing and covered in Section 6.

RATIONALE

The method of fighting wars is changing, and lasers are expected to play an increasingly critical role. In the future we expect to see more short, intense regional conflicts, and our military will seek to project lethal power without putting a large number of forces at risk. Massed forces will be replaced by the massed firepower of lasers and precisely placed munitions on targets. Optics and lasers are constantly encountered in military systems, from low-cost components to complex and expensive systems, and have dramatically changed the way wars are fought. Sophisticated satellite surveillance systems are a keystone of intelligence gathering. Night-vision imagers and missile-guidance units are allowing our armed forces to “own the night.” Lasers are used for many applications, from targeting and range finding to navigation and high-power DEWs.

HPLs are used in industry for many applications, including the welding, cutting, and shaping of metals. Their ability to provide enough energy at the surface of a remote target to drill holes and destroy structures, and to do this at the speed of light, is useful to the military. HPLs with lethal energy for missile applications include CO_2 lasers, as well as chemical lasers and chemical transport lasers, such as chemical oxygen-iodine lasers (COIL), hydrogen fluoride (HF) lasers, and high-powered, solid-state lasers. The military has found applications for HPLs in both tactical and strategic programs. Four applications of HELs in military programs were identified at a recent DDR&E seminar on emerging technologies (December 10, 1999):

- Airborne laser (ABL) using a COIL device for killing missiles in the boost phase.
- Tactical high-energy laser (THEL), a ground-based deuterium fluoride (DF) device to protect civilian population and military assets against missile attack.
- Space-based laser (SBL) using an HF device for missile defense.
- Ground-based, solid-state laser for point defense.
- Airborne tactical laser, a COIL device for attacking ground- and sea-based platforms.

Other applications of military systems that employ long-wavelength lasers are those that seek to facilitate the conduct of military operations at night or under conditions of limited visibility and those used for guided munitions. These critical military applications include the following:

- Ranging—for artillery systems helicopters and armored vehicles;
- Target designation—day/night;
- Semi-active guidance—for laser guided weapons;
- Imaging—for target acquisition;
- LELs—for electro-optic and photonic applications; and
- Infrared countermeasures (IRCM).

Many lasers currently employed on the battlefield, as well in air and in naval military systems, mainly use Nd:YAG-based lasers. These operate in the near-visible region (approximately 1,000 nm). They can be easily detected by most night-vision systems, but they are capable of sensor blinding as well as eye blinding. Consequently, a new family of “eye safe” lasers has been introduced for a number of applications (e.g., range finders, target illuminators). These operate between 1,000 and 2,000 nm.

Lasers are currently incorporated as part of guided ordnance such as laser-guided bombs. LELs have found utility on the battlefield for covert communications, ranging, and aim-point selection and have the capability to temporarily blind or daze personnel. They are used as illuminators in conjunction with low-light imaging systems. LELs with a wavelength between 1.3 and 1.55 μm have applications in very long-distance fiber-optic communications, providing links for command and control. Moderate power lasers are used for in-band sensor blinding to negate optically augmented ordnance. HELs and HPLs are being developed as long-range and short-range lethal weapons for target destruction or mission abortion. Principal military applications for HEL and HPL lasers are space-based DEWs and high-resolution fabrication and material-processing techniques.

DoD has supported laser development from the beginning and has found many applications for the various technologies that were developed. The Desert Storm conflict, and more recently the Kosovo action, pointed out the military's need for the advantage of lasers and optics with laser-guided bombs and night-vision optical sights, both of which provided a significant advantage for the allies.

Today, the applications for lasers range from information technology, profile and distance measuring, and telecommunications, to welding, cutting, and heat treatment, to illuminators and scanners, to medicine, surgery, and health-care applications, as well as specific applications for national defense.

TECHNOLOGY ASSESSMENT

Lasers have become an important focus for new business in the global economy as well as for the military. In the United States, both large and small businesses are significant players in emerging laser technology, and lasers are finding more uses every day in military systems—from weapons applications, to ranging, to information transmission and communications. As the impact of lasers has increased, changes have become necessary in the design, manufacture, and process controls of these new technologies to provide affordable fieldable systems.

The use of commercial laser technologies is important in the overall affordability of a military component or system; however, many commercially available laser products require special parameters or special adaptations to meet military needs. These special DoD operational requirements, combined with the need for only limited quantities, dictates the need for continued DoD support of these research and manufacturing technologies.

Technology has driven each military era's definition of precision. In the 21st century, it will be possible to find, fix, or track and target anything that moves on the surface of Earth using lasers. This emerging reality will change the conduct of warfare and the role of air, land, sea, and space power.

WORLDWIDE TECHNOLOGY ASSESSMENT

Many industrialized nations have the technological know-how to produce specialized lasers for use in both military weapon and nonweapon roles. Several smaller countries are making inroads into the laser rangefinder market cutting the U.S. and Russian share. The United States and Russia have the broadest overall capability in lasers. Whereas the UK, France, Germany, Japan, and Israel have specialized capability in selected types of commercial and military lasers and optics, at least 75 percent of the militarized countries in the world today have deployed some nonweapon lasers. Most of these systems use Nd:YAG lasers at 1,064 nm. (This wavelength can damage the unprotected eye.) The number of nations with a capability to produce the newer eye safe lasers (wavelengths greater than 1,200 nm) is still limited because of limited dual-use or commercial applications.

It is clear that defense against ballistic and cruise missiles is an increasingly important element of U.S. national security. The rapidly growing theater and global threat posed to the United States and U.S. interests by cruise and ballistic missiles of third world countries is accelerating the national interest in developing a defense architecture to counter this threat. Optical surveillance and guidance systems, partnered with high-power lasers, are believed to be effective for theater and ballistic missile defense. New and developing technologies in the laser and optics disciplines are increasing at an exponential rate worldwide. Many of our allies, as well as our adversaries, have the capability to develop advanced laser technologies for military applications. Many are pursuing one or more key technologies that are of utmost importance to our military. As a result, this technology assessment will include any known developing technology that the international community is pursuing.

Country	Sec. 11.1 Lasers
Australia	●
Canada	●●●
China	●●●
France	●●●
Germany	●●●
Hungary	●
India	●●
Israel	●●
Italy	●●
Japan	●●●
Netherlands	●
Norway	●
Russia	●●●
Singapore	●
South Korea	●
Sweden	●
Taiwan	●
Ukraine	●
UK	●●●
United States	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Figure 11.1-1. Lasers Technology Systems WTA Summary

BACKGROUND

A laser is a device which produces a beam of light that is monochromatic and highly directional. In practice, however, one always observes light with a small spread of frequencies even under the best conditions. Also, although to a first approximation all the energy (photons) is emitted in the same direction, in actuality there is a small beam divergence (but not like that from an ordinary light source such as an incandescent light bulb).

Laser light is also highly spatially coherent, which, when combined with the single frequency output, allows interference effects. The divergence from a laser is nearly a diffraction-limited ($\theta \approx \lambda/D$) beam when observed far from the source and a long time after emission. Thus, laser light is quite different from ordinary light, and it has been used in many unique applications.

There are many different types of lasers and many different applications. These applications require different levels of energy in the beam or perhaps different pulse-time sequences. Control of the beam and pulse size is also important and can be adjusted, as required, by selecting the laser and the appropriate operational parameters. Some lasers are large and produce a lot of power. Others are small, require less power, and produce less power. A laser pointer produces a spot on a wall that we can see; a high-powered COIL or CO_2 laser produces a hole that we can see through, in a few seconds, in a 1-in. thick sheet of metal. How much variation in or control over the wavelength, power, coherence, and pulsing sequence is available today and what can we expect to be able to achieve in the future? This is the question we are trying to answer in this document, and it is paced by development of efficient and reliable pump sources.

History

The invention of the ammonia maser in 1954 initiated an era of intense competition in a search for new sources of coherent radiation. The first success was the ruby laser in 1960. It was followed by many devices, which spanned the spectrum from IR to UV. Their emissions were highly directional and of great spectral purity. The development of lasers has been continuously supported by DoD since the beginning. Much effort was devoted to finding new sources at increasingly shorter wavelengths and higher intensities. The driving forces have included scientific curiosity, the need to observe increasingly smaller structures, improving submicron lithography, and obtaining better directed-energy beams for industrial and military uses. The X-ray regime, employing atomic transitions, was reached. The search for systems capable of producing lasing with nuclear transitions continues.

Laser Types

At present, there are available probably thousands of lasers of all types, and many others are in various stages of development. There are several ways of classifying lasers. For the purposes of our discussion, we can divide the field into the type of active medium used: gas, liquid, solid state (condensed matter), and plasma. Nuclear isomers have also been suggested for γ-ray lasers, and the research is proceeding, but these have not been developed yet. There are also concepts based on special approaches, which are more esoteric (i.e., free electron, gas dynamic, exploding wire, and flame).

Gas Lasers

- *Neutral Atomic*—Excited by weakly ionized dc- and rf-excited discharges, pulsed-afterglow discharges, and short-rise-time pulsed discharges (i.e., He-Ne laser).
- *Ionized Gas*—Excited by large dc or rf discharge (i.e., argon ion, HE-Cd, krypton).
- *Molecular*—The CO_2 laser is a good example. It can also be used to pump other molecular lasers, producing output further in the IR.
- *Chemical and Chemical Transfer Lasers*—A system in which the lasing species is produced by the formation or breaking of chemical bonds on a reaction, regardless of how the reaction is initiated.
- *Excimer Lasers*—Use heteronuclear and polyatomic excited molecules to produce UV light at high efficiency and peak powers.
- *Transfer Lasers*—A compound (oxygen) is chemically excited to an excited level (the O-singlet Δ state) by a chemical reaction (usually involving hydrogen perioxide). The lifetime of the excited state (oxygen) is quite long, and it is collisionally mixed with another species (iodine) to form the laser excited state (COIL) concept).

Liquid Lasers

- *Dye Lasers*—One can get lasing by optically pumping a dilute solution or organic dye. The main advantage of dye lasers is that they can be tuned. Because dyes have fast relaxation times, they generally require very intense and rapid pumping—either by flashlamp or another laser.

Solid-State Lasers

- *Semiconductor*—Generally lower power, highly divergent lasers operating at LN_2 temperatures.
- *Color Center, or F-center*—Low-power devices pumped by AR+ or KR+ lasers. These lasers use color centers in alkali halide crystals.
- *Insulating Crystal* (such as Nd:YAG)—These lasers are usually flashlamp pumped. In addition to Nd, there are many other rare earth dopants to produce other laser wavelengths. As the cost of diode pumping approaches $1–2/W, the technology will be utilized more extensively.

Others

- *Free electron laser*
- *X-ray laser*
- *γ-ray laser*
- *"Jet flow" or "gas dynamic" laser*

- *Other lasers based on different storage and excitation techniques such as:*

  – plasma excitation

  – exploding wires

  – shock waves

  – nuclear isomer energy storage.

Applications

In medicine, lasers are used to cut like a scalpel, to destroy cells by heating, and to join cells together—like welding tissue. Lasers used as a scalpel have at least two advantages. They do not introduce bacteria into the cut, and they seal the blood vessels by coagulating the blood—dry cutting. Lasers are also used for eye surgery to correct vision and for observation of internal regions of the body.

Use lasers and fiber-optics, instead of electrical impulses and wires, revolutionized communication. More information (2–3 orders of magnitude) can be carried by 100 times lighter carriers as a result.

Laser beams are used in construction by engineers to guide machinery and to measure distances.

In industry, lasers are used for highly accurate cutting (parts for motor vehicles), welding (fine focusing produces fine welds), and drilling holes in metal.

In space applications, lasers have been used to measure distances in space and to study shifting of continents on Earth from locations in space.

Using holographic techniques, lasers can be used to make three-dimensional images of objects.

Laser technologies have matured in the specialized telecommunications information technology arenas and in three-dimensional image-storage devices. Optics and electro-optics research technologies are now the predominant emerging technologies in the laser optics field of disciplines.

The military uses laser for communication, for designation of targets to be tracked or destroyed, and as weapons.

Other military applications of lasers span the electromagnetic regions from the UV to the IR. This diversity of coverage requires a wide range of technologies. Each wavelength regime demands different materials, and each poses different technical challenges. The following lists some of these applications:

- Rangefinders, especially those which are eyesafe.
- Target designators.
- Laser radar for target acquisition, homing, and obstacle avoidance.
- LIDAR for biological /chemical detection and identification.
- Laser-based countermeasures, especially at mid-IR wavelengths.

The laser weapon concept has been demonstrated both on the ground and in airborne configurations. At first glance, high-power lasers would seem to serve only military needs; however, advances in these technologies have provided many other uses for scientific and commercial applications.

SECTION 11.1— BACKGROUND SUPPLEMENT I: FREE ELECTRON RADIATORS[1]

It has been known for a long time that accelerating charged particles convert part of their kinetic energy to electromagnetic radiation. Several experimental arrangements that have been devised to show this effect provide effective and in some cases practical sources of coherent EM energy. We list some of them here.

A. SYNCHROTRON RADIATION

This radiation occurs when electrons are guided in circular orbits at high energies in accelerators. Since the 1940's, synchrotrons have played an important role in nuclear and high-energy research.

The three leading synchrotron radiation sources (SRSs) in the United States, existing or planned, are the Advanced Photon Source to be constructed at the Argonne National Laboratory, the Cornell High Energy Synchrotron Source (CHESS), and the National Synchrotron Light Source (NSLS) at the Brookhaven National Laboratory. The following tabulation gives some important parameters for these SRSs and the Stanford Synchrotron Radiation Laboratory (SSRL) source:

Source	Energy (GeV)	Current (mA)	Peak Field (kG)	Bending Radius (m)	Ec (keV)
APS*	7.0	100	6	39.0	19.6
NSLS	2.5	250	12	6.87	5.0
CHESS	5.5	75	5.7	32.0	11.5
SSRL	3.0	100	7.9	12.6	4.7

* The Advanced Photon Source to be constructed at the Argonne National Laboratory. There are plans to use a positron beam in APS. The other sources accelerate and store electrons.

B. CHERENKOV RADIATION

Cherenkov radiation is produced when a charged particle traverses a dielectric medium at a speed exceeding the speed of light in that medium. The radiation is produced by a collective motion of the particles in that medium as they point toward the passing particle (electron).

Both Russian and American groups have studied the Cherenkov effect and have used it to construct light sources tunable from the infrared to the soft X-ray regime. A Stanford group (Ref. 1) has used the electron beam at the Stanford linear accelerator (SLAC), together with a 7-m long gas cell containing helium at low pressure, as well as air at somewhat higher pressures.

C. COMPTON BACKSCATTERING

In 1923, A.H. Compton discovered that X rays scattered by atoms consist of two components. One component is radiation of the incident wavelength; the other, the so-called modified component, consists of radiation of a longer wavelength.

In recent years, major research centers both here and abroad have been causing beams produced by high-energy electrons to collide with intense photon beams from lasers. In 1975, the Frascatti National Laboratories (Ref. 2) initiated a project to produce an X-ray source suitable for photonuclear research in the few-to-many-MeV regime. An argon ion laser and the Adone electron storage ring were united to produce what is referred to as the LADON photon beam.

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1 Material in this section is taken from Cohen, L., "Free-Electron Radiators," IDA Paper P-2993, December 1989.

D. WIGGLERS

The wiggler (or undulator) is a magnetic structure which has been used for many purposes: to enhance synchrotron radiation, to amplify laser radiation, and to generate the spontaneous radiation as a component of a free-electron laser (FEL).

Wigglers were incorporated as part of the plans for the development of new synchrotron radiation sources; however, in recent years, they have played a more prominent role as a major component of a FEL. With the probable exceptions of the SRS and Compton backscattering, each type of radiator discussed in this section could, in principle, be placed in a suitable resonant cavity and be made into a lasing device. This possibility became a fact for the wiggler in 1977 when the Stanford group (Ref. 3) first generated and amplified optical radiation in the near IR.

E. CHANNELING RADIATION AND COHERENT BREMSSTRAHLUNG

In analogy with the man-made wiggler, nature provides periodic structures with which charged particles can interact to produce tunable monoenergetic radiation. Channeling radiation (CR) occurs when the incident beam is so nearly parallel to the crystal planes that the particles channel. As the misalignment angle is increased, a critical angle is reached when the coherent bremsstrahlung (CB) begins to dominate the X-ray spectrum.

Much theoretical and experimental work on CR and CB was done in the 1980's, and many of these studies were performed in the GeV regime. Most of the research was devoted to work with thin crystals. One Russian group (Ref. 4) has reviewed previous work on the prospects of producing a γ-ray laser based on channeling. The work was extended to include the consideration of a visible laser, with the conclusion that both γ-ray and visible lasers would be difficult to develop at present because of constraints of current density.

F. SMITH-PURCELL RADIATION

Smith-Purcell radiation occurs when an electron is forced to move at right angles to the ruling of a conductive grating. An image is induced in the grating and oscillates with the periodicity of the grating. The moving dipole moment produces the radiation.

Since the initial discovery of this effect, much theoretical work has been carried out both here and abroad to extend the very simple theory of Smith and Purcell and to attempt to structure infrared and millimeter radiation sources based on Smith and Purcell. In 1960, di Francia (Ref. 5) explained the radiation somewhat differently: a relativistic electron produces an electromagnetic field which is resolved into Fourier amplitudes; the amplitudes, representing evanescent waves, are attenuated with distance from the electron; and the latter waves are diffracted by the grating to form the Smith-Purcell radiation.

G. TRANSITION RADIATION

Transition radiation occurs when a charged particle crosses the boundary between two media of different dielectric constants. Frank and Ginsburg predicted this phenomena in 1946. In 1959, the phenomena was observed by Goldsmith and Jelly.

In the early 1980's, the Stanford group studied the production of soft-to-hard X rays using various foils and both electron and positron beams with energies ranging from tens of MeV to several GeV. Soft X-rays ranging from 0.8 to 2 keV were produced with 90 MeV electrons and stacks of beryllium, mylar, and aluminum foils (Ref. 6), and X-rays from 2 to 6 keV were observed with mylar stacks and electrons at 66 and 104 MeV (Ref. 7). Later, 4-GeV positrons were used to produce peaks at 11.6 and 12.8 keV (Ref. 8), and a tunable source was produced by rotating the stack through angles from 0 deg to 60 deg, thereby moving the peak from about 10 keV to about 20 keV (Ref. 9). In all of the above work, results were in agreement with calculations and led to a study and a proposal (Ref. 10) to use transition radiation (TR) as a tunable source of X rays.

Recently, the properties of TR have been applied as diagnostics to study the characteristics of particle beams. Using e-beams ranging from 63 to 97 MeV (Ref.11), coherent and incoherent angular distributions were observed and compared for equally spaced and randomly spaced mylar stacks.

H. REFERENCES

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SECTION 11.1— BACKGROUND SUPPLEMENT II: X-RAY LASERS

OVERVIEW

The concept for X-ray lasers goes back to the 1970’s, when physicists realized that laser beams amplified with ions would have much higher energies than beams amplified using gases. In X-ray lasers, a pulse of light strikes a target, stripping its atoms of electrons to form ions and pumping energy into the ions (“exciting” or “amplifying” them). As each excited ion decays from the higher energy state, it emits a photon. Many millions of these photons at the same wavelength, amplified in step, create the X-ray laser beam. The highly ionized material in which excitation occurs is a plasma

The shaded area of Figure 11.1-2 shows the region of the EM spectrum that is of interest in X-ray laser research in general. This region stretches roughly from about 100 nm to less than about 0.01 nm. Although ions with transitions that emit hard X rays at higher energies exist and could possibly support lasing, the majority of the research effort has been spent on this X-ray energy region.

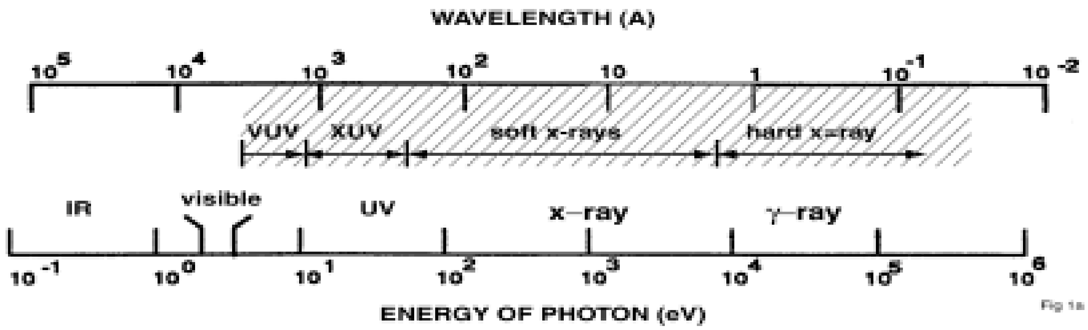

Figure 11.1-2. The X-Ray Laser Region of the Electromagnetic Spectrum

Most applications of X-ray lasers fall into one of four categories, although some overlap into more than one:

- Scientific applications (investigations of atomic structures, nuclear decay modification, and radioactive chemistry);
- Technical applications (preparation of small structures-gratings/grids, spectroscopy of solids, and metallurgy);
- Biomedical applications (microscopy, holography radiography in vivo or at least in the natural state); and
- Military applications.

Military applications range from production of components, using lower energy X-rays, to X-ray weapons using higher energy X-ray lasers. Laser weapons will project coherent electromagnetic energy to a distant target at the speed of light. Such beams have been suggested for exoatmospheric applications. We concentrate on concepts that rely on conventional (nonnuclear) pumping processes because these seem the most promising. Certainly more research has been devoted to these concepts, but they are limited to photon energies below 1 keV, in the range of 10 to 10^{-9} keV, although other concepts, with the potential of producing more energetic photon beams, have been proposed.

RATIONALE

An X-ray laser beam delivers energy at the speed of light; however, scattering and absorption impose limits on the distance over which short-wavelength EM beams can propagate through the atmosphere. Therefore, in industrial applications, X-ray lasers can only be used at close distances in air for material analysis and modification. In space, which permits longer ranges, X-ray lasers can be used as a weapon.

Energy from visible, UV, or even soft X-ray (long wavelength, low photon energy) is deposited on the surface. At shorter wavelengths the energy is deposited more deeply in the target, over a range that depends on the wavelength or photon energy. This adds another dimension to the kill mechanism/CM considerations when the laser is considered as a weapon. Also, the deeper penetration in solid materials is useful in analytical work and in industrial applications.

The short wavelength of X-rays coupled with the coherence properties, directionality, and intensity of lasers is necessary for holography and crystallography of small structures like static atoms. The short time pulses (on the order of 10^{-12} to 10^{-15} sec) are required and invaluable for studying the dynamics of these structures.

BACKGROUND

The invention of the ammonia maser in 1954 initiated an era of intense competition among members of the scientific community in a continuing search for new sources of coherent radiation. Beginning with the ruby laser in 1960, many new sources of electromagnetic radiation began to appear. Their emissions are highly directional and of great spectral purity. Wavelengths range from about 1 mm to about 1 nm; power levels, to greater than 1,012 W. All of these devices depend upon electromagnetic transitions between pairs of precisely located quantum levels in an ensemble of atoms, of molecules, in crystal lattices, or upon the interaction of electron beams with man-made structures. Gain depends on the amplification produced by the stimulated emission of radiation from an inverted population of the level pairs and on the feedback supplied by a pair of precise mirrors in a resonant cavity. Much effort was devoted to finding new sources at increasingly shorter wavelengths and higher brightness. The driving forces behind this effort have included scientific curiosity, the need to observe increasingly smaller structures, improving submicron lithography, and obtaining better directed-energy beams for industrial and military uses. This drive led to the X-ray regime and, ultimately, to gamma-ray lasers. In the X-ray case, except for harmonic-generation techniques, those quantum states comes into play that are located in atoms either deprived of their inner electrons or made highly charged by having outer electrons stripped off.

THE X-RAY REGIME

Atomic energy levels to a good approximation are inversely proportional to the square of the principle quantum number and the square of the mass or nuclear charge. Photons with energies in the X-ray region are generally obtained from transitions between inner core electronic levels. In the dentist's office, X-ray images are produced by using as a source a tungsten target bombarded by electrons. A small number of ions are generated, and X-rays are emitted. In the process, a small number of tungsten atoms are ionized and quickly neutralized. To get lasing, a larger number of atoms have to be ionized to produce an inversion first. Thus, to produce an X-ray laser, both the power requirement and inversion condition lead naturally to plasma as the active medium.

The X-ray regime of the EM spectrum is a difficult part of the spectrum to deal with in generating a laser. First of all, the resonant cross-section decreases with the square of the frequency (inverse square of the wavelength), imposing more severe requirements on the pumping power, and photon emission is severely inhibited by competition from internal conversion below 1 keV, in the X-ray regime. Working in this high-energy regime introduces other problems not usually encountered at lower energies:

(1) There are no effective mirrors so that one is forced to consider only single-pulse devices.

(2) The short lifetimes of atomic transitions require high pumping rates to obtain inversion.

(3) The high pumping rates and the need to work with inner shell electronic levels restricts the selection of the active medium to plasma, a difficult state to work with.

PUMPING METHODS

Although pumping power requirements are extremely demanding, work continues to extend the lasing region to higher energies. The most recent work in X-ray lasers has concentrated on the following approaches for pumping to inversion.

Collisional excitation with electrons. In this method an electron excites a multiply ionized ion to the upper lasing level, u, which participates in the lasing transition to the lower lasing level, l, as shown in Figure II.1-3(a). The difficulty with this process is that a metastable upper level is required to minimize the effect of the reduction of the inversion by the concurrent population of the lower lasing level by this indiscriminate pumping source.

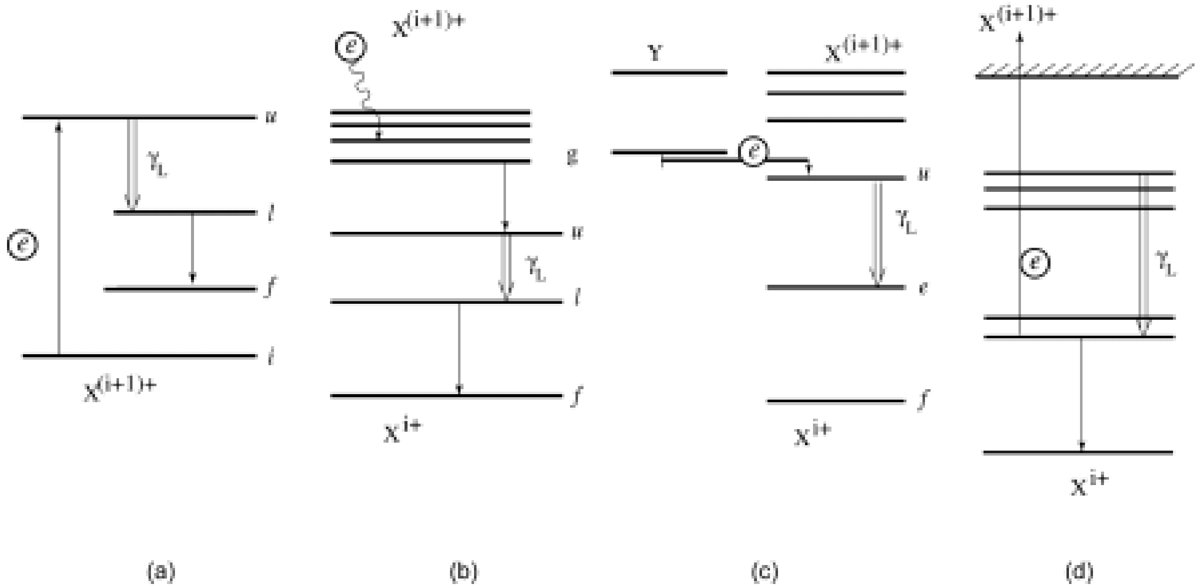

Figure II.1-3. The X- Ray Laser Pumping Schemes

Photoexcitation. In this method [Figure 11.1-3(b)], absorption of photons of the proper frequency provides selective excitation of the upper level while avoiding population of the lower level. The difficulty here is finding a wavelength match between pump and laser ions.

Electron-collisional recombination. This process is the inverse to electron-collisional ionization from excited levels. A free electron is captured in a high bound quantum state of an ion. This is followed by a cascade down to the lower states, resulting in a population density inversion

Charge transfer. In this process, an ion acquires an electron from an atom, rather than a free electron, and ends up in an upper lasing level state. The process is as shown in Figure II.1-3(c), with the exception that an atom is the source of the electron. The process is energy resonant between the binding energies of the electron in the ground state of the atom and that of the upper lasing level.

Electron-collisional ionization. In this process [Figure II.1-3(d)], an innershell bound electron is released through ionization, following an inelastic collision between a free electron and an ion. This process creates an atom in the next lower state of ionization, forcing a transition to the upper lasing level.

ALTERNATIVE APPROACHES

- Harmonic generation and frequency mixing.
- Free electron laser, extension to higher frequencies.
- Others.

EMISSION MODES

At present, because of the lack of adequate mirrors for radiation in the laser regime, the X-ray laser is generally a single-pulse devise. In principle, pulsed X-ray laser emission can occur in two possible forms: superfluorescence (SF) and amplified spontaneous emission (ASE). SF is cooperative spontaneous emission from many nuclei, whereas ASE is the result of a photon spontaneously emitted from a single nucleus and amplified as it propagates through a medium. Both SF and ASE need an inverted medium for their occurrence, although the requirements on SF are more severe and require slower decorrelation processes.

The ASE phenomenon, like SF, can be obtained from an inverted population of atoms or nuclei constrained to an acicular region, and it is initiated by spontaneous emission from a single atom or nucleus. The emitted photon is amplified as it propagates along the axis of the high-gain medium. Spontaneous emissions in other directions are not amplified, so that they affect the ASE pulse propagating along the axis only to the extent that they reduce the inversion and therefore the amplification gain. The axial position of the emitter that initiates the process is a stochastic variable; thus, for a complete treatment of the phenomenon, the emission from all points along the axis must be taken into account. For SF to occur, the emitting dipoles in the system form correlations so that acting collectively as a single dipole they emit a pulse proportional to *N*2, where *N* is the number of cooperating nuclei. Unlike SF, the ASE pulse intensity is directly proportional to *N*. Whether SF or ASE occurs depends on the strength of the dephasing mechanisms that can destroy the correlations between the dipoles necessary for SF.

Generally speaking, the emission of an SF pulse requires the preparation of an inverted population of identical radiators. Experimentally, the emitted pulses are characterized by a pulse width and a delay time, τ_Δ, following the inversion of the population. From simple theory, the relationship between τ_{SF} and and the density of cooperating radiators, ρ, the natural radiative lifetime, τ_0, the wavelength of the emitted light, λ, and the cavity length, l, can be obtained. In terms of these parameters

$$\tau_R = \frac{8\pi\tau_o}{\rho\lambda^2 1} ,$$

$$\tau_D = \frac{1}{2}\tau_R \ln N ,$$

and the pulse intensity Is(t) is given by the “inverted pendulum expression”

$$\mathrm{Is}(t) = \frac{1}{2} N/\tau_R \ \mathrm{sech}^2 \left[\frac{1}{\tau_R} (t - \tau_D)\right]$$

(Ref. 7), where t is measured from the time of the (instantaneous) inversion.

Three regions are delineated according to the magnitude of the dephasing time τ_ϕ (or decorrelation time) relative to the product of τ_D, the delay time, and τ_{SF}, the SF time. Figure II.1-4 shows three different pulses representing SF, ASE, and spontaneous emission without gain as a function of the inverse of the dephasing time, $\tau_{\phi.}$.These pulses were calculated using the Haake-Reibold theory of SF. By varying the dephasing time, one theory produces the variety of pulses expected from an inverted population of resonators.

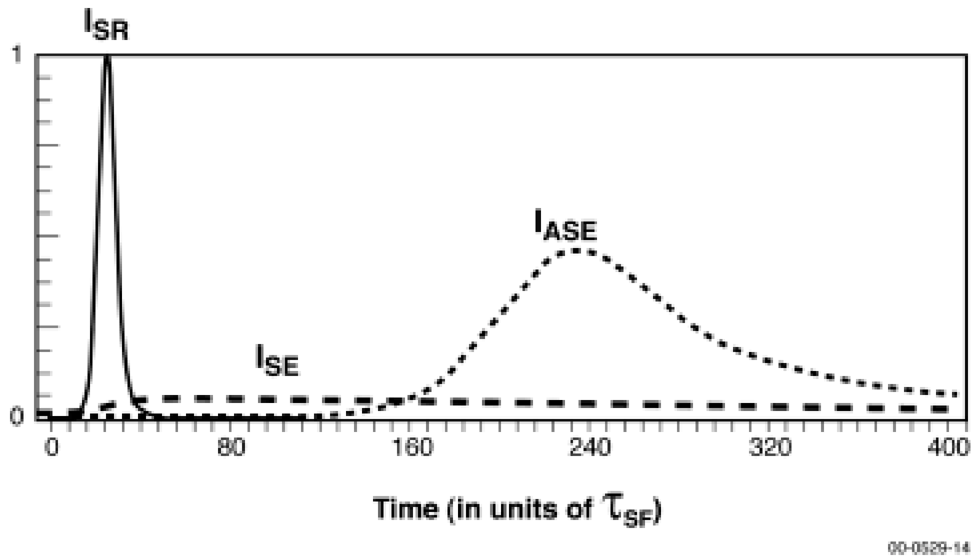

Figure II.1-4. Type of Emission Expected from an Inverted Population of Atoms or Ions

In the SF regime

$$\sqrt{\tau_D \tau_{SF}} < \tau_\varphi \quad ,$$

correlations between emitters develop, and strong pulses are emitted in both directions along the axis. In the ASE regime

$$\tau_{SF} \ < \ \tau_\varphi \ < \ \sqrt{\tau_D \tau_{SF}} \quad ,$$

and correlation between emitters are suppressed by the dephasing mechanisms, but the median still amplifies spontaneously emitted pulses. When $\tau_\phi < \tau SF$ there is no gain in the medium, and only natural decay contributes to the emission. Figure II.1-5 shows how the delay time varies as a function of the inverse of the dephasing time over the three regions SF, ASE, and SE.

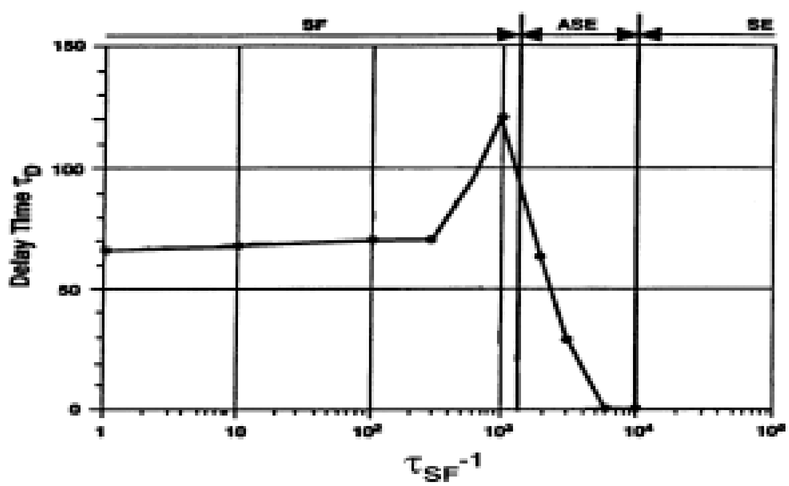

Figure II.1-5. Delay Time of Pulse from an Inverted Population of Resonators τ_D as a Function of the Inverse of the Dephasing Time, $(\tau_\phi)^{-1}$

POTENTIAL APPLICATIONS

Soft X-rays cannot penetrate a piece of paper, but they are ideal for probing and imaging high-energy density ionized gases, known as plasmas. High-energy radiation is capable of deep penetration of dense materials, however. In iron a 1 MeV γ-ray (with an attenuation coefficient of $\mu_a \cong 0.4$ cm^{-1}) has almost 10^6 times the penetration of a 1-keV γ-ray. This feature, together with other characteristic features of photons emitted in nuclear transitions (such as high-energy resolution), and the ability to ionize atoms and molecules, coupled to the attributes of a laser beam (such as high coherence), would permit good focusing at high intensity and could provide a new powerful technique for probing and modifying materials.

The following are some potential applications of γ-ray lasers:

- **γ-ray and X-ray spectroscopy,** where higher energy resolution would permit greater discrimination, while deeper penetration would permit inspection of thicker samples.
- **Holography,** where short wavelength coherent radiation might permit observation of the structures of molecules, crystals, proteins, and genes.
- **Precision frequency measurements,** where measurements based on interferometric techniques could be extended to the nuclear region, thus greatly increasing the precision in the determination of nuclear properties (with possible applications to reactor design and fusion investigations).
- **Imaging techniques (CAT scanners),** where monochromatic radiation would permit lower doses to patients, while higher resolution would allow discrimination between molecular species and not just between density variations.
- **NLO effects** at nuclear energies could be investigated with applications to high-energy particle and nuclear studies.
- **Nuclear reaction modification,** where the high intensity of the highly monochromatic γ-radiation would permit selective removal of electrons and thus charge density modification in and around the nuclear volume.
- **Microscopy and structure determination,** where the high intensity would allow short exposures, and high collimation would permit Fresnel-limited resolution.
- **Microreplication** and fabrication of microelectronic components, where high intensity and excellent collimation will shorten the exposure time and ensure good resolution.
- **Material science,** where the high intensity of the ionizing radiation will provide massive ionization of materials on a local scale, leading to violent structure modification.
- **Diagnostics of fusion pellets,** where the X-ray laser can provide a penetrating probe for the analysis of high-density plasmas which are compressed to ion densities of greater than 10^{27} cm^{-3}.
- **Solid-State Studies** for fine tuning the equation of state of a variety of materials, including those used in making weapons.

Material for this section was obtained from several sources, notably:

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2. ———, *X-ray Lasers,* Academic Press (1990)
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LIST OF TECHNOLOGY DATASHEETS
III-11.1. LASERS

DATA SHEET III-11.1. TRANSFER LASERS (COIL)

Developing Critical Technology Parameter	Critical parameters are complex functions of wavelength, peak power, and average power. The following regimes resulting from different applications can be identified. <u>Required:</u> Power >20 kW for CW laser and energy >1 kJ pulsed laser Wavelength in the range of (0.3–30 µm) <u>Available Wavelength/Bandwidth:</u> DF/$C0_2$—10.6 µm; COIL (Chemical Oxygen–Iodine Laser)—1.3 µm. >10’s kW demonstrated.
Critical Materials	Fuels and fuels handling materials—surface passivated, fluorine compatible. Low-loss glass, fused silica, and silicon for COIL laser optics. Diodes for diode pumping scheme of resonances in oxygen to produce singlet Δ oxygen.
Unique Test, Production, Inspection Equipment	Numerically controlled machine tools. Laser-diagnostic equipment, for >20 kW for CW laser, >1 kJ pulsed laser. Steering-errors testing equipment to <10 µrad. Beam-quality testing equipment. Computer-controlled machinery.
Unique Software	Computer design and operation codes. Codes for beam-target interaction effects. Nonlinear correction at HEL levels. Optical design codes and ray tracing codes. Aerodynamic and solid window design codes.
Technical Issues	Optimization of subsystems to reach required power pulse-rate energies. Laser-beam transmission through atmosphere. Beam-phase conjugation. Beam stabilization, precision phasing, and enhancing laser interaction with system. Production of low-cost diode pumps. Efficient coupling of pump to host. Match of resonator mode volume and pumped region to maximize efficiency. Improvement of flow by advances in design of valves and venturis. Improvements in combustion theory and experimental work. Improvements in aeroflow path, theory, and design. Understanding of target interaction physics and kill assessment: – Power and energy required to kill target, – Nature of the failure mode and type of kill, and – Laser wavelength and pulse format related to vulnerability parameters.

Technical Issues (continued)	Introduction of diode pump to excite oxygen state at resonant wavelength. Heating problems with diode optical pumping scheme.
Major Commercial Applications	Remote sensing. Welding and material forming. Fabrication.
Affordability	Not applicable.

RATIONALE

At high energy and power, this system will provide a long-range lethal weapon for target destruction or mission abortion in space-based defense. Short wavelength means less diffraction spreading. It will provide capability for disabling missiles, satellites, or airplanes. This laser can also be used for midcourse discrimination and/or soft kill.

WORLDWIDE TECHNOLOGY ASSESSMENT

China	●	Czech Republic	●	France	●●	Germany	●●
Israel	●	Italy	●	Japan	●●	Russia	●●
UK	●●	United States	●●●				

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The United States is a leader in this research with a significant effort, and UK, France, Japan, Germany, and Russia with moderate to limited R&D.

BACKGROUND

Oxygen is chemically excited to the O-singlet Δ state by a chemical reaction, usually involving hydrogen peroxide. The lifetime of the excited oxygen is quite long, and it is collisionally mixed with iodine to form laser-excited state. Iodine may be in form of CF_3I or C_5F_7I (iodated freons), which have a higher vapor pressure at room temperature than pure I_2. When lower level of iodine ion recombines, it reforms donor molecule and hence can have a closed-cycle laser.

DATA SHEET III-11.1. EXCIMER LASERS (LELs)

Developing Critical Technology Parameter	Critical parameters are complex functions of wavelength, peak power and average power. The following regimes resulting from different applications can be identified. General: Power >1 kW average and wavelength in the range of 0.8 µm–0.5 µm Power >1 kW average at 455 or 486 nm 70 J/pulse discharge Specific: Wavelength/Bandwidth — ArF (0.19 µm) generally narrow lines KrF (0.24 µm) generally narrow lines Xe Cl (0.385 µm) generally narrow lines XeF (0.35 µm) generally narrow lines F(0.13 µm) generally narrow lines
Critical Materials	Optical coatings. Foil support made from special high-strength maraging steel (also used for torpedos).
Unique Test, Production, Inspection Equipment	Numerically controlled machine tools. Laser diagnostic equipment for >1 kW for CW laser and >1 kJ pulsed laser. Beam quality testing equipment. Computer-controlled machinery.
Unique Software	Computer design and operation codes. Codes for beam-target interaction effects. Nonlinear correction at HEL levels. Optical design codes and ray-tracing codes.
Technical Issues	Optimization of subsystems to reach required power pulse-rate energies. Laser beam transmission through atmosphere. Beam phase conjugation. Beam stabilization, precision phasing, and enhanced laser interaction with system. Match of resonator mode volume and pumped region to maximize efficiency. Understanding of target interaction physics. – Power and energy required to kill target, – Nature of the failure mode, type of kill, and – Laser wavelength and pulse format related to vulnerability parameters.
Major Commercial Applications	Underwater communications and imaging. High-resolution lithography. Fabrication.
Affordability	Not applicable.

RATIONALE

This system will be useful for high-resolution lithography, in the range of 0.18–0.25 µm feature sizes, underwater communication and imaging, and ground-based space applications.

WORLDWIDE TECHNOLOGY ASSESSMENT

Canada	●	China	●●	France	●●	Germany	●
Israel	●	Italy	●●	Japan	●●	Russia	●●
UK	●●	United States	●●●				

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The United States is a leader in this research with significant R&D, followed by the UK, France, Japan, China, Italy, and Russia with moderate to limited R&D.

BACKGROUND

Electron-beam dissociates rare gas (Kr, Ar) and halide (F_2 or CI_2) and forms dimer (excimer) in excited state, e.g., KrF*. Upon emission of a photon, dimer ion decoys to ground state which is unstable (shallow or no potential well). Ions split up leaving Kr, Ar and F_2- or Cl_2- (which reform F_2 + $C1_2$).

DATA SHEET III-11.1. NOVEL <111> PIEZOELECTRIC OPTOELECTRONIC DEVICES FOR 1.0–1.3 μm LASER WAVELENGTH RANGE

Developing Critical Technology Parameter	New or improved reliability laser diodes with 1.0–1.3 μm emission on GaAs substrates. New 1-V optoelectronic absorption modulator exploiting the piezoelectric (PE) effect for operation at 1.0–1.3 μm. Natural integration/coupling of lasers, waveguides, and modulators. Optoelectronic switches with gain. Enabling technology for integrated optoelectronic circuits exploiting exciton transport. Future integration of III-V optoelectronic devices with Si electronics. Possibility of giant quantum-well (QW) structures for long-wavelength devices on GaAs: terabit intersub-band optical switching at 1.6 μm and novel thermophotovoltaic (TPV) devices based on piezoelectric-quantum well infrared photodetectors (PE–QWIPs) for conversion in the 1.7–4.0 μm. Piezoelectric sensors and their integration with optoelectronic devices.
Critical Materials	High In content InGaAs (In > 30%) on polar <111> gas. InGaAs/gas/AlGaAs strained QW with piezoelectric field on <111> GaAs with high optical quality. For device structures, highly conductive n- and p-type gas and AlGaAs layers with device quality surfaces on <111> GaAs.
Unique Test, Production, Inspection Equipment	Metal organic vapor phase epitaxy (MOVPE) or molecular beam epitaxy (MBE) epitaxial fabrication. Optical spectroscopy: Photoluminescence and photoreflectance. X–R spectroscopy. Electron microscopy.
Unique Software	None identified.
Technical Issues	The envisaged device applications relate to (1) the existence of a large PE field in <111> QW structures; (2) a larger critical layer thickness (CLT) for <111> orientations compared with conventional <100>; and (3) the achievement of very high-quality heterointerfaces. Excellent <111> QW device structures have been achieved at $\lambda \approx 1.0$ μm by CU and a few other groups in the world. Further R&D will be needed to extend λ to ≈ 1.3 μm and other wavelength ranges. Long-wavelength ($\approx$ 1.3 μm) emission and modulation have not been achieved using GaAs substrates at the level of practical applications. The realization of a practical 1.3 μm laser diode and modulator on a GaAs substrate would lead to integration of optoeletronic devices and reduction in product costs. Low voltage (<1.5 V) modulator theoretically demonstrated but not developed yet. PE-field can be exploited to produce a high ratio of ON/OFF wavefunction overlap even at low voltage.
Major Commercial Applications	Satellite and optical-fiber communications. Energy conversion.
Affordability	Uses present GaAa fabrication technology (see Section 8).

RATIONALE

This technology could replace the cathode-ray tube (CRT) as the standard for information display in many military and commercial applications. In addition, analog SLMs with world-class performance for optical signal processing and image analysis would result from this work. The high-resolution potential and high efficiency of this mass-producible technology warrants increased development funds.

WORLDWIDE TECHNOLOGY ASSESSMENT

France	●●	Germany	●●	Israel	●	Italy	●
Japan	●●●	Russia	●●	South Korea	●●	Spain	●●
Sweden	●●	Switzerland	●●	Taiwan	●●	UK	●●●
United States	●						

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Japan and the UK are leaders in this field with significant R&D, followed by France, Sweden, Germany, Russia, Switzerland, South Korea, Taiwan, and Spain.

DATA SHEET III-11.1. SURFACE-EMITTING LASERS

Developing Critical Technology Parameter	Technology of grating coupled surface-emitting GaAs and AlGaAs laser diodes is a continuing, ongoing development with a number of different manufacturing technologies, including tapered gratings and circular gratings. Some applications require these lasers to be steerable. Being developed are 1.55-µm distributed Bragg reflectance (DBR) lasers using grating coupling, which have the potential for high-power, low-divergence, rapid-steering, low-weight devices in the data link operation as well as eye-safe operation.
Critical Materials	Circular gratings and tapered gratings on surface emitters and transparent indium-tin oxide electrode material.
Unique Test, Production, Inspection Equipment	Long-distance pointing and tracking testing with millisecond response.
Unique Software	Mode selection and the dynamics of steerable grating coupled surface-emitting lasers.
Technical Issues	Mode control of the lasers, array of high-power steerable lasers, high-speed modulation.
Major Commercial Applications	Space and terrestrial communications.
Affordability	Need to reduce the cost significantly in large-volume production.

RATIONALE

Many surface emitting laser diodes are being developed. The advantages to this technology are that higher power, low divergence, and rapid steering should be achieved using the grating coupling technology. This technology has both affordability issues and technology issues. Long-range communications require 1.55-µm laser sources with low divergence and outputs above 100 mW for eye safety and low atmospheric absorption. This technology would provide a significant improvement to current laser communication devices. This technology will provide very compact, lightweight, steerable laser modules for jamming-free optical links between stationary or mobile objects and rapid deployment in remote areas.

WORLDWIDE TECHNOLOGY ASSESSMENT

Canada	●	China	●●	France	●●	Israel	●
Japan	●●●	Russia	●	Singapore	●	South Korea	●
Taiwan	●	UK	●	United States	●●●		

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Japan, China, and the United States are leaders in this field, followed by Canada, Israel, South Korea, Taiwan, France, Russia, the UK, Germany, and Singapore.

DATA SHEET III-11.1. MID-IR LASERS

Developing Critical Technology Parameter	High average power diode pumped solid-state lasers with frequency agility/diversity in the 2 to 5 μm spectral region with closed loop operation. 2.0 W per line at 20 kHz pulse repetition frequency (PRF) in Band I. 2.0 W in Bands III and IV. Lightweight (total system weight of 20 lb or less). Cryocooler with better than 10 W at 77 K. High brightness and high beam quality at all power levels (5–7 × diffraction limit).
Critical Materials	Low optical absorption optical parametric oscillator (OPO) materials for all three wavelength bands. High-efficiency phase conjugation material. New, high-efficiency lasers are needed, including diode-pumped semiconductors. Low thermal distortion OPO materials need to be developed. Only U.S. ZGP material with acceptably low absorption has been demonstrated.
Unique Test, Production, Inspection Equipment	Diode array far-field power and spatial distribution testing equipment. M^2 beam quality measurements.
Unique Software	None identified.
Technical Issues	High average power with high-efficiency frequency conversion in the 2–5 μm region has not been demonstrated. Laser diode array efficiency and average power level must be improved. High average power pump lasers are required to meet military system requirements for remote sensing. Thermal effects must be minimized in zinc germanium phosphide (ZGP) and other OPO materials at high PRF.
Major Commercial Applications	Since the primary requirement is for a bright laser source in the mid-IR for counter-measure applications, it is not clear what direct commercial applications might result. Improving the efficiency of OPOs and reducing the cost and weight of the devices will spin off many of these technologies to commercial application.
Affordability	Affordability must be addressed at all levels of development to provide DoD with logistic options.

RATIONALE

The top three Service Priority List items concern infrared countermeasures (IRCM) issues. There have been significant advances in OPO materials and new lasers in the last few years, providing a basis for optimism that a mid-IR laser system can be developed. An agile mid-IR laser for CM and counter-countermeasure (CCM) purposes is desperately needed. All three Services have major programs on hold until this technology is developed. This set of technologies needs to be worked in concert to maximize trade-offs during the technology-development phase. The decision to proceed into the engineering-development phase with an OPO or direct semiconductor must be made within the next fiscal year. Dilution of critical funds to carry multiple approaches is a problem. Direct semiconductors that can be made to operate efficiently at 120 K is a requirement which needs to be developed.

WORLDWIDE TECHNOLOGY ASSESSMENT

France	●	Germany	●●	Israel	●	Japan	●
Norway	●	Russia	●	South Korea	●	Sweden	●
Taiwan	●	UK	●●●	United States	●●●●		

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

There is significant to extensive R&D effort in the United States and the UK. Only U.S. ZGP material with acceptably low absorption has been demonstrated. Germany is sponsoring moderate R&D, while other nations sponsor limited R&D.

DATA SHEET III-11.1. EDGE-EMITTING LASER DIODE ARRAY PROCESS TECHNOLOGY

Developing Critical Technology Parameter	Laser diode arrays are currently hand-labor intensive. Automation and process technology need to be developed to provide a more cost effective and reliable product. It is imperative that oxidation be carefully controlled during the soldering process to prevent debonding. Process technologies that need to be developed include bar metalization and mounting technologies, gold/platinum soldering process technology with minimal diode degradation, uniform pitch process technology (nominally 200 µm), and mounting procedures that eliminate voids in the metallization and soldering processes.
Critical Materials	AlGaAs, InGaAs, and GaP.
Unique Test, Production, Inspection Equipment	M^2 (beam quality) measurements to within less than 1 percent of diffraction-limited quality and spatial distribution measurements of arrays. Everything should be 100 percent inspected. It is critical to apply a proper testing procedure for the mounted arrays, as well as to the individual diodes, to ensure reliability of mounted diodes in the future use of the device.
Unique Software	None identified.
Technical Issues	Previous mounting technologies have left voids in the soldering layer, causing premature failure to the device. Hand lay-up of the arrays has proven too costly to be competitive with other illumination sources for many applications. An automated mounting process must be developed that is efficient and provides high yield.
Major Commercial Applications	Night light sources for police and security guards, welding, optical pumps, laser surgery sources, ship mast illumination, printing drums, and telecom are currently being considered.
Affordability	If automation process technology can be achieved with pick-and-place equipment and the gold/platinum soldering, then a cost-effective mass-produced array will be available.

RATIONALE

Currently, both the military and commercial sectors need significant cost reduction in the manufacturing of laser diode arrays for applications ranging from welding to optical pumping sources for laser rangefinders and remote lighting sources in submarines or on ship masts. Many other diode array lighting applications will become cost effective once the benefits of this proposed manufacturing technology (cost reduction factors of 8 to 10) are demonstrated. This development will be a significant economical boost to the EO industry and provide a much needed resource for the military.

WORLDWIDE TECHNOLOGY ASSESSMENT

Canada	●	China	●	Finland	●●●	France	●●●
Germany	●●●	Israel	●	Italy	●	Japan	●●●
Netherlands	●	Norway	●	Russia	●●	Singapore	●
South Korea	●	Sweden	●	Switzerland	●	Taiwan	●●
Ukraine	●	UK	●●	United States	●●●		

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The United States, France, Germany, Finland, and Japan have significant R&D efforts. The UK, Taiwan, and Russia are behind, with moderate efforts.

DATA SHEET III-11.1. SOLID-STATE LASERS (HELs)

Developing Critical Technology Parameter	Critical parameters are complex functions of wavelength, peak power, and average power. The following regimes resulting from different applications can be identified. <u>Required</u> Power >20 kW for CW laser and energy >1 kJ pulsed laser. Wavelength in the range of 0.3 µm–30 µm. <u>Achieved</u> Wavelength/bandwidth Typically 1.03 µm (ytterbium), 1.05 µm (yttrium), or 1.06 µm (neodymium). Power Level 100,000 J/pulse from NOVA laser at Naval Research Laboratory (NRL) in an energy storage mode. 3.6 MJ planned for Natural Ignition Facility laser (LLNL). Russians reported >10 kJ in literature; for Δt >2/msec, 1 MJ.
Critical Materials	Very pure glasses and crystals for host materials. Fusion bonded composite (doped and undoped) laser materials.
Unique Test, Production, Inspection Equipment	Numerically controlled machine tools. Laser diagnostic equipment. Steering errors testing equipment to <10 µrad. Beam quality testing equipment.
Unique Software	Computer design and operation codes. Codes for beam-target interaction effects. Nonlinear correction at HEL levels.
Technical Issues	Optimization of subsystems to reach required power pulse-rate energies. Computer -controlled machinery. Laser beam transmission through atmosphere. Beam phase conjugation. Beam stabilization, precision phasing, and enhancing laser interaction with system. Production of low-cost but high-reliability (long lifetimes) diode pumps. Efficient coupling of pump to host. Match of resonator mode volume and pumped region to maximize efficiency. Improvement of flow by advances in design of valves and venturis.
Major Commercial Applications	Laser fusion. Industrial applications.
Affordability	Not applicable.

RATIONALE

This system will provide capability for disabling missiles, satellites, or airplanes. This laser can also be used for midcourse discrimination. In addition to CM applications, this laser can be used for range finders, target designators, and remote sensing.

WORLDWIDE TECHNOLOGY ASSESSMENT

China	●	France	●	Germany	●●●	Israel	●
Japan	●●●	Russia	●●●	UK	●●	United States	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The United States has best developed diode pump and crystalline composite materials. Russia has nonlinear technology, including phase conjugate MOPA. Germany and Japan are close behind the United States. There is considerable interest in 5–7 kW lasers for industrial use. Russia and Ukraine have strength in phase conjugation, and their nonlinear optics are the best in the world. Cooperation with the United States makes for some real transparency on HEL solid-state lasers.

BACKGROUND

Optical pumping into absorption based of laser ion causes a population inversion. (For Yb:YAG λ_p = 950 nm and λ_L = 1030 nm.) After ion lases, ions in lower state rapidly decay to ground state nonradiatively.

DATA SHEET III-11.1. SOLID STATE LASERS (LELs)

<table>
<tr><td>Developing Critical Technology Parameter</td><td>Solid-state lasers are rugged, lightweight, and readily available in a number of powers and wavelengths in both rod and slab geometry.

Common materials include Nd:YAG and neodymium-glass (Nd:glass). Tunable solid-state lasers are made from alexandrite and titanium.

All lasers can be frequency doubled (or multipled) by the use of nonlinear crystalline materials that create harmonics of the input frequency.

<u>Power</u>
Flashlamp-pumped (CW powers in the kilowatt range)
Diode-pumped (10s of W).
Laboratory systems (100s W to 1 kW)

<u>Achieved:</u> Some characteristics of some lasers

Alexandrite (0.7–0.9) µm Highly tunable
Er:Yb:Glass 1.54 µm Eyesafe wavelength
Ho:YAG 1.05 µm CW to a few W
Nd:Glass 1.054 µm Pulsed to 100 W
Nd:YLF 1.047 µm CW or pulsed to 10s of W
Nd:YV04 1.06 µm CW to I0s of W
Ruby 0.69 µm Low rep-rate but high-energy pulses
Trn:VAG (1.7–2.006) µm CW to a few W
Ti:sapphire (0.67–1.07) µm Broadly tunable</td></tr>
<tr><td>Critical Materials</td><td>Solid-state lasers typically use crystalline material, such as YAG or YLF, or are glass doped with a rare earth or metal ion (Nd, Er, Cr) as the lasing medium.

Common materials include Nd:YAG and neodymium-glass (Nd:glass). Tunable solid-state lasers are made from alexandrite and titanium.

Common materials used in diode-pumped solid-state lasers are Nd:YAG, Nd:YLF and, more recently, Nd:YVO.</td></tr>
<tr><td>Unique Test, Production, Inspection Equipment</td><td>Numerically controlled machine tools.</td></tr>
<tr><td>Unique Software</td><td>None identified.</td></tr>
<tr><td>Technical Issues</td><td>Efficiencies of solid-state lasers need to be raised. At present, range from less than 1 percent for some flashlamp-pumped systems to 10 percent for diode-pumped Nd:YAG systems.

Efficient and reliable diode pumps and growth of high-purity, defect-free crystals with high optical quality are the most critical issues.

Temperature control is a limiting factor in obtaining high powers. Temperature gradients generate thermal lensing phase aberrations and diffractive losses.</td></tr>
</table>

Major Commercial Applications	Fabrication. Micrography. Medical/biological imaging in vivo or at least in realistic sample environments. Long-range biological standoff detection. Low-power scanners (mW). Medium-power medical (W). High-power industrial cutting tools (MW). Materials processing—annealing, cutting, welding, marking, bonding, drilling, heat-treating and alloying, and robotics. Medical/biomedical—arthroscopy, orthopedics, photocoagulation, plastic surgery, general surgery, cancer treatment, dermatology, obstetrics, angioplasy, ophthalmology, and otorhinolaryngology.
Affordability	Not an issue.

RATIONALE

At the high end (energy, power, frequency), this system will provide near-instantaneous kill, warhead detonation, structural breakup, and electronic upset. Effective as a weapon for space applications and for material modification at ground level. Knowledge of the physics of target interaction is useful for offensive and defensive system designers but for different reasons. For offense, this knowledge can improve system design and operation; for defense, can improve protection through innovative materials design.

WORLDWIDE TECHNOLOGY ASSESSMENT.

Country	Laser Systems	Diode Arrays	Nonlinear Materials
Australia	●●		
China	●●		●●●
France	●●	●●	●●●●
Germany	●●	●●	●●●
Israel	●●	●●	
Japan	●●●●	●●	●●
Russia	●●●		●●●
UK	●●		●●
United States	●●●●	●●●	●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Figure 11.1-1. Solid State Lasers Technology Systems WTA Summary

The United States and Japan are leaders in laser system development, diode array development, and nonlinear materials research. The United States has a slight lead in diodes, and China has extensive R&D work in nonlinear materials.

DATA SHEET III-11.1. OPTICALLY PUMPED LASERS

Developing Critical Technology Parameter	Critical parameters are complex functions of wavelength, peak power and average power. The following regimes resulting from different applications can be identified. λ <150 nm, E >50 mJ/pulse, peak power >1 W. 150 nm <λ < 800 nm, E >1.5 J/pulse, peak power >30 W. 800 nm <λ < 1,400 nm, E >0.5 J/pulse, peak power 50 W. λ >1400 nm, E >100 J/pulse, pulsed peak power 1 W.
Critical Materials	Titanium-doped sapphire, alexandrite, DCR^{4+}:YAG, and other solid-state g-switch materials; two engineered materials such as periodically poled $LiNiO_3$ and fusion-bonded composites (i.e., doped and undoped YAG); and $YalO_3$ and sapphire. Optical pumped semiconductors (GaSb). High-power/high-reliability diode pumps. High-power optical coatings, low-loss optical material, and space-qualified components.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Computer design and operation codes. Codes for beam-target interaction effects.
Technical Issues	Optimization of subsystems to reach required power pulse-rate energies. Beam phase conjugation. Production of low cost, but reliable (long life), 2 µm diode pumps. Efficient coupling of pump to host.
Major Commercial Applications	Underwater imaging, remote sensing, and surgical applications. Medical underskin surgery.
Affordability	As optically pumped semiconductors are operated at higher temperatures (above 110 K), the system cost/volume complexity are all reduced.

RATIONALE

At the high end (energy, power, frequency) this system will provide capability for disabling and/or destroying sensors. In addition to CM applications, this laser can be used for range finders, target designators, and remote sensing.

WORLDWIDE TECHNOLOGY ASSESSMENT

Canada	●●	China	●●●	France	●●●●	Germany	●●●
Israel	●●	Italy	●●	Japan	●●●	Russia	●●
UK	●●	Ukraine	●●	United States	●●●●		

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Many countries have R&D efforts in optically pumped lasers or in supporting technologies. France has strength and extensive R&D in precision optics (RIOSC). France, Germany, the UK, and Italy have significant R&D

in new materials, and especially diode-pumped solid-state lasers. China has strength in materials development. Israel uses U.S. diodes in its diode-pumped solid-state lasers. Russia and Ukraine have strength in phase conjugation, and their nonlinear optics are the best in the world. Cooperation with the United States makes for some real transparency on HEL solid-state lasers.

DATA SHEET III-11.1. X-RAY LASERS

Developing Critical Technology Parameter	Beam Generation: amplified spontaneous emission, superfluorescence Available: Wavelength: 3–4 nm Energy: ~mJs Efficiency: 10^{-6} Pulse width: to ps range Directions of work: Multiphoton ionization Shorter pulsed lasers Technology for laser-produced plasmas Electric discharge technology Desired achievements: Wavelength: ~ –100 to 0.1 nm (concepts using plasma as active medium) Pulse Length: 10^{-12} to 10^{-15} sec or shorter Energy Stored/Power Out (depends on transition energy and inversion): 5×10^{14} W/cm^3 pump irradiance. >10 cm^{-1} laser linear gain coefficient. Beam Intensity: >5.0×10^{11} W/cm^2 Application requirements: Scientific: –100 to 0.1 nm, 10^{-12} to 10^{-15} sec Technical: 0.5–2 nm (fabrication) Biological/Medical: 0.1–100 nm (spectroscopy) Military: >1 nm
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Ion source preparation technology. Precision plasma technology. Precision plasma measurements.
Unique Software	Computer design and operation codes. B-field and E-field mapping codes.
Technical Issues	Optimization of subsystems to reach required power pulse rate energies. Work concentration on smaller, table-top lasers, implying lower power lasers. Work on more energetic/powerful lasers needs to be pursued. Multiphoton ionization technology needs to be developed. Concepts for shorter pulsed lasers need to be developed—especially for biological/ scientific applications. Technology for laser-produced plasmas. Electric discharge technology. Improvement in beam quality—especially for lithography.

Major Commercial Applications	Micrography. Medical/biological imaging in vivo or at least in realistic sample environments. Welding, material forming.
Affordability	Not applicable.

RATIONALE

At the high end (energy, power, frequency) this system will provide near instantaneous kill, warhead detonation, structural breakup, and electronic upset. An X-ray laser is effective as a weapon for space applications and for material modification at ground level. Knowledge of the physics of target interaction is useful for offensive and defensive system designers but for different reasons. For offense, this knowledge can improve system design and operation; for defense, can improve protection through innovative materials design.

At the lower end, X-ray lasers will extend scientific investigations of fast dynamic processes in solids, liquids, and biological molecules. In industry, speedier fabrication will be possible at higher resolution of electronic and electro-optical components.

WORLDWIDE TECHNOLOGY ASSESSMENT

France	Germany	Japan	United States
●	●	●●	●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The research on X-ray lasers in the United States has been declining since the 1990's, with no major work funded at present. There are small efforts at Lawrence Livermore National Laboratory (LLNL) and at Colorado State University (building on 1990's successes). As far as foreign research and development is concerned, there is a small effort in France; a small, declining effort in Germany; but in Japan there is a good solid research effort directed toward lithography, with some interest in biological applications.

DATA SHEET III-11.1. GAMMA-RAY LASERS*

Developing Critical Technology Parameter	Beam Generation: nuclear SF, ASE Wavelength: ~ 1 to 0.01 nm (concepts using recoilless emission) ~ 1 nm and below (gas graser concept—single phonon emission) Lifetime of Isomeric Level: ~ 100 sec to 1,000 sec (concepts using direct emission from isomeric level) ~ 1,000 sec and above (upconversion concepts) Temperature: ~10^{-9} K (for gas graser concept) Energy Stored/Power Out (depends on transition energy): > 5×10^{8} J/cm^{3} > 5×10^{10} W Beam Intensity: >5.0×10^{11} W/cm^{2} Status: λ-ray laser is in theoretical, concept development state. Some experimental work on upconversion concept performed recently claimed observation of enhanced emission from Hf isomer. This is controversial. Developments in nanotechnology show promise for preparation of clean (very low level inhomogeneous broadening) samples and specially designed crystals for active media to reduce attenuation. This would enhance possibility of observing lasing using the concept of direct emission from isomeric levels.
Critical Materials	Isomeric nuclei with closely spaced levels (0.1 eV to 100 keV). Isomeric nuclei with Moessbauer transitions.
Unique Test, Production, Inspection Equipment	Numerically controlled machine tools. Nuclear source preparation technology. Precision nuclear measurements. Ultra low temperature technology (<10^{9} K). Technology for manipulation and control of individual atoms.
Unique Software	Computer design and operation codes. Accelerator cavity alignment inspection code. B-field mapping codes. Computer codes for accelerator design. Magnetic beam line design.
Technical Issues	Optimization of subsystems to reach required power pulse-rate energies. Computer-controlled machinery. Beam control.
Major Commercial Applications	Charged particle beam (CPB) fusion. Inertial fusion. Nuclear defense simulation and hardening test. Welding and material forming.
Affordability	Not applicable.

* See Section 6 for background.

RATIONALE

This system will provide near-instantaneous kill, warhead detonation, structural breakup, and electronic upset. A gamma-ray laser is effective as a weapon for space applications and for material modification at ground level. Knowledge of the physics of target interaction is useful for offensive and defensive system designers, but for different reasons. For offense, this knowledge can improve system design and operation; for defense, can improve protection through innovative materials design.

WORLDWIDE TECHNOLOGY ASSESSMENT

Belgium	●	France	●	Germany	●	Russia	●
Ukraine	●	United States	●●				

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

There is a limited to moderate effort in the United States to extract energy from nuclear isomers as a precursor to lasing. Some experimental work was also done in Germany and France.

In Russia and Ukraine the work is mostly of theoretical nature, dealing with concept development and investigation of esoteric propagation effects.

DATA SHEET III-11.1. LASERS IN THE 3–15 μm RANGE

Developing Critical Technology Parameter	Diode-pumped and optically pumped lasers are needed in the 3–15 μm wavelength region, where chemical and biological contaminants and drugs absorb radiation. IR CM against heat-seeking missiles is a very critical issue. Candidate lasers such as lead salt lasers and the inter-subband quantum cascade laser have shown promise at lasing beyond 3 μm. Type II diodes with AlGaAsSb broadband-waveguide separate confinement regions in quantum wells recently became the first electrically pumped lasers in this region and have shown increased gain and efficiency. At 300 K, a 10 quantum well device had a peak output power greater than 2 mW and a lasing spectral width of 12 nm centered at 3.3 μm wavelength. CW operation has been achieved at 170 K with an output power of 68 mW. These optically pumped Type II devices with rotationally symmetric active regions (called "W" configurations) recently attained the highest cw operating temperatures of any semiconductor lasers emitting between 3 and 6 μm. Lasing action has been obtained out to 7.3 μm, which is 2 μm beyond the previous interband III-V lasing compound.
Critical Materials	High purity Type II "W" configuration materials are needed to demonstrate higher efficiency.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Technical Issues	Research is necessary to optimize the optical pumping injection cavity structures, such as GaSb/AlAsSb distributed Bragg reflectors, which are required above and below the "W" well active region. This etalon cavity, required for the pumping beam, has been shown to increase the absorptance to as high as 56 percent. Higher absorptance should be possible providing higher efficiencies.
Major Commercial Applications	Laser spectroscopy, laser surgery, and infrared illuminators are the prime candidates.
Affordability	Since all of the physical layup is done via thin-film and molecular beam epitaxy (MBE) deposition, the process should produce cost-effective devices once the technology is better understood and tradeoffs are established as the operating temperature increases.

RATIONALE

Currently, semiconductor diodes dominate the market for near-IR lasers; longer wavelength devices emitting beyond 3 μm are needed to provide chemical and biological detection of gases and drugs as well as IRCMs against heat-seeking missiles or imaging systems.

WORLDWIDE TECHNOLOGY ASSESSMENT

China	●	France	●	Germany	●●	Japan	●●
UK	●	United States	●●●				

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The United States is the leader in this technology, with Germany and Japan closely following.

DATA SHEET III-11.1. PHOTONIC CRYSTAL NANOCAVITY LASERS

Developing Critical Technology Parameter	Two-dimensional photonic crystals have been microfabricated into InGaAsP slabs, which constitute the smallest lasers to date. These lasers produce lasing, which is then wave-guided in a thin membrane and reflected in the lateral direction to define a high-Q laser cavity. The waveguiding is done with high index contrast slabs in which light can be efficiently guided. Microfabricated two-dimensional photonic bandgap mirrors provide the geometries needed to confine light into extremely small volumes with high Q. Thus, two-dimensional Faby-Perot resonators with microfabricated mirrors are formed when hole defects are introduced into the periodic photonic bandgap structure. Defects are introduced into the periodic photonic bandgap structure and then used to tune these cavities lithographically by changing the precise geometry of the micro-structures surrounding the defect. High Q values in the range of 15,000 to 25,000 have been measured in these crystals. These lasers can operate at room temperature in volumes as small as 0.03 μm^3 in InGaAsP emitting at 1.55 µm with a 1-µW nominal peak output power. The critical technology parameters concern the understanding of the defect requirements on the geometry of the cavity and improved coupling techniques. It is important to find techniques to decrease these cavity mode volumes even more because it is known that the coupling efficiency and the lasing mode can be significantly improved. The spontaneous emission coupling efficiency can also be improved if the linewidth of the semiconductor emission is narrowed. High-coupling techniques are needed to improve this technology to provide faster modulation response and lower lasing thresholds.
Critical Materials	Typical InGaAsP devices are structured with four 9- to 10-nm thick InGaAs quantum wells separated by three 20-nm thick InGaAsP barriers and InGaAsP layers on the top and bottom of the quantum wells. InGaAsP material has been chosen since it does not suffer from large surface recombination losses and is relatively easy to microfabricate with the desired structural features. Other similar material composites will also be utilized during the optimization processes.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Technical Issues	Optimization of the microfabrication of the laser cavities. These lasers suffer from heating problems. Precise optimization of the laser wavelength by means of the lithographic process and subtle changes in the microstructures adjacent to the cavity, which can also determine the direction of the laser output. Optimization of the lasing frequency through changes in the lattice parameters.
Major Commercial Applications	Many, including optical computing and optical integrated circuits.
Affordability	This technology should be very affordable since all steps of the process can be envisioned as additional steps in the chip-manufacturing process.

RATIONALE

This laser technology has great potential for “on-chip” manufacturing for optical loops and switches. The laser output can be easily coupled into photonic crystal waveguides within the photonic crystal structure. Note that multiple wavelength emitters can be arranged on a single membrane array via variance in the defects and cavity structures. This permits tens to hundreds of discrete wavelengths in the 1.4 to 1.6 µm range with this material composition for wavelength discrimination requirements. This technology has evolved to a level that allows the control of light within etched microstructures. New technology that is under way will optimize the output and directionality while improving the efficiency. With laser cavity sizes far below a cubic wavelength, it is now possible to couple them together into coherent systems and provide additional advantages from cavity quantum electrodynamic effects and coupling. The next step is to use this technology for the design of active and passive devices. These laser cavities provide functionality in the form of filters and laser resonators, as well as the building blocks for miniaturized photonic integrated circuits.

This technology has the potential to revolutionize integrated circuits and optical processors, as they are known today, and to provide a significant improvement in optical computing endeavors.

WORLDWIDE TECHNOLOGY ASSESSMENT

China	●	France	●	Germany	●	Japan	●●
Norway	●●●	Russia	●	Taiwan	●	UK	●
United States	●●●						

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The United States and Norway have the lead in this technology, with Japan closely following.

DATA SHEET III-11.1. MID-IR, CW, POWER-SCALABLE FIBER LASER

Developing Critical Technology Parameter	This is a compact, tunable, high-efficiency mid-IR laser that has been demonstrated to produce 40 mW at a wavelength of 2.7 µm with 780 nm Ti:Al_2O_3 laser pump. With diode pump at 980 mm, it achieved 10-mW operation. Experiments at 980 nm indicated no saturation of output so the laser can presumably be scaled to higher levels. It is estimated that the laser can be scaled to produce watt power levels at wavelengths of 2.7 µm. The laser uses a double-clad fiber 5.5 m long with Er:ZBLAN center as the lasing medium. Ability to tune the laser has been demonstrated over 50 nm.
Critical Materials	Double-clad Er:ZBLAN fiber.
Unique Test, Production, Inspection Equipment	Numerically controlled machine tools. Doped-fiber fabrication technology.
Unique Software	None identified.
Technical Issues	Identification of new/alternative fiber material. Increase of efficiency, achieving higher power. Determination of limits on scalability. Increase photon coupling efficiency to fiber core.
Major Commercial Applications	Fabrication. Micrography. Medicine: general surgery, cancer treatment, dermatology, obstetrics, angioplasty, and ophthalmology. Environmental monitoring of industrial gases (NO, H_2S, ozone).
Affordability	No information available (TBD).

RATIONALE

This particular laser has great potential for military applications in the field because it is compact, efficient, and tunable. It can be used for mid-IR countermeasures, monitoring the environment for toxins, and in medical applications for field diagnostics and surgery because of the strong absorption of 2.7 µm in human tissue.

WORLDWIDE TECHNOLOGY ASSESSMENT

France	●	Germany	●	Japan	●	Russia	●
UK	●	United States	●●●				

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The United States is a leader with a significant R&D effort, followed by Japan, UK, France, Germany, and Russia with limited efforts.

DATA SHEET III-11.1. DOUBLE-CLAD FIBER LASERS

Developing Critical Technology Parameter	The double-clad or dual-clad fiber laser is compact, tunable, and highly efficient. The fiber creates an optical laser cavity that can be tens of meters long with a large area for heat dissipation. This, together with double cladding, permits high-power operation. The double-clad fiber geometry ensures high pump light absorption, leading to high pumping efficiencies (>60 percent). Yb fibers are the most efficient (>70 percent). Two claddings—each with different index of refraction—allows efficient power consumption. No cooling is required at low powers. At higher powers cooling needed, as heating at 1.5 °C/W of power observed. Good spectral and spatial quality is observed, and the system maintains diffraction-limited beam quality independent of system age or environmental changes. 55-W output power at 1,110 nm has been demonstrated. The potential for 10–100 kW output power is anticipated. Rare-earth doped fiber is used as the active medium. The fibers can be – Neodimium-doped (for visible-near IR) – Ytterbium-doped (1,080 nm) – Erbium-doped (1,560 nm) – Thulium-doped (1.7–2.006 µm). Erbium/ytterbium co-doped fibers provide better utilization of pump power and thus attain higher efficiency. Ytterbium broadbands (920–980 nm) absorb the pump light (from multimode diode lasers) and transfer resonantly to erbium atoms.
Critical Materials	Neodimium-doped fiber. Ytterbium-doped fiber. Erbium-doped fiber. Thulium-doped fiber. Co-doped fibers like ytterbium/erbium. YAG fibers. Phosphate glasses.
Unique Test, Production, Inspection Equipment	Numerically controlled machine tools. Doped-fiber fabrication technology.
Unique Software	None identified.
Technical Issues	Identification of new dopants. Identification of new fiber-cladding geometries. Identification of new/alternative fiber material. Increasing efficiency, achieving higher power. Overcoming ion clustering and ion pair quenching.

Major Commercial Applications	Micromachining—welding, bonding, soldering, stress relieving, and heat treatments. Magnetic and optical storage—semiconductor and electronics industry. High-power amplifiers—communications industry. Telecommunications. Materials processing. Medicine—general surgery, cancer treatment, dermatology, obstetrics, angioplasty, and ophthalmology.
Affordability	No information available (TBD).

RATIONALE

Because of their high power, compact design, efficiency, and ability to be tuned, double-clad fiber lasers have great potential for military applications in the field. They can be used for countermeasures, monitoring the environment for toxins and other hazardous materials. In medical applications they can be used for field surgery and diagnostics; they are especially durable.

WORLDWIDE TECHNOLOGY ASSESSMENT

China	●	France	●	Germany	●●	Japan	●●
Russia	●	UK	●●	United States	●●●		

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The United States is the leader, followed by Japan, UK, and Germany, which have moderate research programs underway.

BACKGROUND

The dual-clad fiber has revolutionized fiber laser power levels.

The current state-of-the-art demonstration has been at 110 W at SDL, Santa Clara, California. The AFRL has a number of efforts with SDL funded and underway and is looking at kilowatt-capable fiber laser devices. Single-fiber laser devices have been operated at the 100-W level, and the United States is pursuing kilowatt-capable, single-element fiber lasers at this time. Arrays of fibers are being pursued with the anticipated power levels of 1–100 kW capabilities 5 or more years into the future.

Research worldwide is occurring, predominantly in the following locations:

- *UK (moderate R&D)*—Southampton University (D.J Richardson), Manchester University, Fibercore (commercial), and others.
- *Germany (moderate R&D)*—IRE-POLUS Group (commercial).
- *Japan (moderate R&D)*—NTT Photonics Lab.
- *United States (significant R&D)*—AFRL and funded small businesses (fewer than one dozen) and collaborating laboratories (NRL, MIT/LL, LLNL). All others are limited R&D.

There is a shortage of components to conduct research in this area. For example, the number of facilities to draw the fibers is limited:

- SLD Cambridge (former Polaroid);
- NOI/ION (Canada);
- Spectran (now purchased by Lucent);

- Lucent (Spectran and Lucent are not commercially involved with DC fiber devices or components);
- Boston University (Ted Morse); and
- Kigre (with Rutgers University for phosphate glass fibers).

Lucent has indicated a willingness to participate with the government to supply limited quantities of DC fibers and components. Spectran has experience in this area of DC fibers; Lucent has experience with the components only. Components such as isolators, gratings, circulators, phase modulators, etc., do not exist for Yb-doped fiber wavelengths. A significant increase in funding in this area is needed to stimulate U.S. research in this technology area.

DATA SHEET III-11.1. ULTRA-FAST FIBER LASERS

Developing Critical Technology Parameter	The ultra-fast fiber laser is compact, tunable, highly efficient, and rugged. A typical system comprises an erbium-doped fiber laser oscillator and an erbium-doped fiber amplifier followed by a frequency doubler. No cooling is required. Diode lasers provide the pump energy, and the fiber creates an optical laser cavity that can be tens of meters long with a large area for heat dissipation. The laser system is relatively temperature insensitive. Operates over 30 °C temperature range (around room temperature) without user adjustments. The system can be made compact. A 20 by 20 by 10 cm package can produce 100 to 200 femtosecond pulses with an average 10 to 25 mW. For comparison, a bulk laser with this repetition rate would require a free space optical path length of 3 m. Emission from erbium-doped fiber is at 1,550 nm. Good spectral and spatial quality is observed and the system maintains diffraction-limited beam quality independent of system age or environmental changes. Fiber-based architecture makes the laser relatively free of thermally induced beam wandering. Beam pointing stability is 1 μrad, typically.
Critical Materials	Erbium-doped fiber. Other rare-earth doped fibers.
Unique Test, Production, Inspection Equipment	Numerically controlled machine tools. Doped-fiber fabrication technology.
Unique Software	None identified.
Technical Issues	Identification of new dopants. Identification of new fiber-cladding geometries. Identification of new/alternative fiber material. Increasing efficiency, achieving higher power. Overcoming ion clustering and ion pair quenching.
Major Commercial Applications	Biological imaging with two photon scanning microscopy. Telecommunications. Medical diagnostics. Medicine: general surgery, cancer treatment. High-speed circuit testing of high-speed electronic devices. Terahertz measurements using coherent detection instead of power detection. Hyperspectral imaging in the terahertz regime. Detection of gases in flames. Inspection of injection-molded plastic. Mapping of doping concentrations in silicon wafers.
Affordability	Cost is not a major factor.

RATIONALE

Ultra-fast fiber lasers have great potential for military applications in the field because of compact design, efficiency, and durability. They can be used for monitoring the environment for toxins and other hazardous materials. In medical applications they can be used for field surgery and diagnostics; they are extremely durable and unaffected by changes in the environmental conditions.

WORLDWIDE TECHNOLOGY ASSESSMENT

China	●	France	●	Germany	●	Japan	●
Russia	●	S. Korea	●	UK	●	United States	●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The United States is the leader in the R&D and production with a significant effort. Japan, China, Russia, France, Germany, UK, and South Korea have limited R&D involvement. A significant effort is dedicated to analog-to-digital conversion with high repetition and short pulse rate.

DATA SHEET III-11.1. ORGANIC SEMICONDUCTOR THIN-FILM EDGE-EMITTING LASERS

Developing Critical Technology Parameter	Laser action in thin-film organic semiconductors has been demonstrated. Both semiconductor waveguide and double-heterostructure devices were used. Edge effect emission was observed. Efficient, long-lived, and intense electroluminescence in both polymeric and small-molecular-weight organic thin films motivated the search for laser action in these materials. Optical pumping in both semiconductor waveguide and double-heterostructure devices was used, indicating a new class of electrically pumped laser diodes may be possible. The thin-film active material for both geometries was tris-(8-hydroxyquinoline) aluminum (Alq3) doped with 2.5-percent DCM (laser dye). The slab optical wave guide laser was grown on InP substrate pre-coated with a 2-nm-thick layer of $SiO_{2,}$ deposited by plasma-enhanced chemical vapour deposition. A 300-nm-thick film of Alq3/DCM (with optical index of refraction n = 1.7) formed a slab optical waveguide, with SiO_2 (n = 1.4) as a cladding layer on one side and air (n = 1) on the other. The double heterostructure in-plane waveguide was made by sandwiching a 50-nm-thick film of Alq3/DCM between two 125-nm-thick Alq3 cladding layers. All conducting organic layers produce both electrical and optical confinement, which idicates that lasing may occur under electrical injection. The pump was a pulsed nitrogen laser beam ($\lambda = 337$ nm). Threshold pump energy was ~ µJ cm^{-2} for a 5-mm-long double-heterostructure laser. These lasers, at λ = 645 nm, in vacuum-deposited organic semiconductor thin films are characterized by high efficiency (70 percent), narrow-linewidth (< 0.1 nm), high-output-power (> 50 W) lasing at λ = 645 nm in vacuum-deposited organic semiconductor thin films. The pump threshold for an electrically pumped laser made from organic double heterostructures is estimated at 10 nm cm^{-2}.
Critical Materials	Tris-(8-hydroxyquinoline) aluminum (Alq3) doped with 2.5-percent DCM (laser dye).
Unique Test, Production, Inspection Equipment	Numerically controlled machine tools. Plasma-enhanced chemical vapor deposition.
Unique Software	Not determined.
Technical Issues	Identifying new/alternative thin-film material. Increasing efficiency, achieving higher power. Determinating limits on scalability. Increasing photon coupling efficiency to thin film. Methods of electrical pumping the thin-film structures. Demonstrating electrically pumped laser action.

Major Commercial Applications	Communications. Opto-electronic devices (see Section 11.5).
Affordability	Not determined.

RATIONALE

This particular laser has great potential for military applications in the field where opto-electronic devices are required (see Section 11.5) because it is compact, efficient, and tunable.

WORLDWIDE TECHNOLOGY ASSESSMENT

Austria	●	Germany	●	Japan	●●	UK	●
United States	●●●						

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

In this technology, the United States is the leader, followed by Japan. The remaining countries, Germany, Austria, and UK, have a basic capability.

SECTION 11.2—OPTICS

Highlights

- Micro-optics will begin complementing and then replacing electronic components on chips, reducing heat and improving speed and throughput while reducing cost.
- Nanotechnology will result in significant improvement in electro-optics and nonlinear optics, which will have widespread military applications.
- Continued advances in optical coating material technologies will result in improved hardness capability of various military optics hardware.
- Reducing the weight of technology for space optics, vital to our space requirements, will be addressed by numerous new technology applications of high-strength composites.
- Integrated design, fabrication, test, and assembly methods will permit the transition of today's hybrid optical devices into the fully integrated optical systems required for miniaturization and high performance in future products.
- Real-time, computer-controlled optical grinding and polishing, along with micropolishing, will cut the time required to fabricate aspheric optics by a factor of 10 or more.

OVERVIEW

Optics and optical systems are used for military applications ranging from surveillance, navigation, and night vision systems to fiber-optic communications and display technology. Optics has become the pervasive enabler for a significant number of other disciplines such as telecommunications, physical security, and more recently data storage and optical computing. This subsection covers the broad discipline of developing optics, optical materials, and optical component technologies, which are envisioned to be of critical military utility once developed.

This section includes those technologies ranging from night-vision optics and lightweight space optics to improved process technology for aspheric lenses, reflectors, and nonconformal optical surfaces, as well as developing technologies for nonlinear and fiber optics. The optical material technologies include new development, refinement, and production processes for metal and dielectric optical substrates, as well as new optical composite materials. The optical materials will also include developing technology in crystalline and organic nonlinear optical materials. Developing technologies in the area of optical substrates, including ceramics, low-thermal-expansion glass, metals, and optical composites will also be addressed. Optical systems technologies will be presented here if they are generic in nature; otherwise, they will be referenced if covered in one of the sections of this report.

BACKGROUND

The impact of optics has increased significantly in the last few years. Major changes have been necessary to improve component utility while improving efficiency and reducing costs by means of mass production process technologies and greater use of computer design and fabrication technologies. These changes have manifested themselves in ways that were not even dreamed of 20 years ago, but which today significantly affect the way optical components and systems are now designed, fabricated, and tested. As recently as a decade ago, most optical components were made in small specialty optics firms with the support of master opticians. This was the result of stringent specifications required by the military and other government agencies as well as many scientific researchers. At that time, however, the market was not big enough to support the costs of developing mass-production process technologies. In some cases, the technologies being developed today were not even a gleam in the optician's eye, let alone contemplated.

Today, thanks in a large part to the ever-expanding commercial sector, which uses optics and optical components, optical manufacturing technologies are seeing a resurgence, and new process technology is under way. This continual maturing of optical technologies has permitted a new focus, that of micro-optics technologies, which are now enabling complex systems to be constructed in areas such as spatial light modulators, integrated opto-electronic arrays, opto-electronics, and quantum opto-electronics at the chip level. In addition, fiber-optic components and systems represent an area in which commercial investment has led the way for DoD applications. Basic data-transmission systems have been adapted and improved for battlefield environments, with the commercial sector leading the technology development. The use of fiber-optics on aircraft, satellites, ships, and submarines has started to expand following similar commercial successes. This increased utility of fiber-optics along with optical imaging technologies and optical storage devices is pushing the technology envelope in related areas such as optical parametric amplifiers and nonlinear optical materials development for waveguide and switching applications in the micro-optics field.

The performance of almost all optical and electro-optical material is critically dependent on the quality, composition, and dimensional control of the materials used in the manufacturing process. Every stage of crystal growth, material processing, and device fabrication requires stringent control of defects, interfaces, and layer-deposition rates. A precise knowledge of the interrelationships among material quality process parameters and device performance is also needed. As is well known from laser-absorption studies and subsequent laser damage studies, reducing absorption in optical materials has a major impact on optical components such as high-energy laser optics and space optics. Absorption will probably have a significant impact on micro-optics because of the very thin optical paths and waveguides that are used.

Considerable progress has been made in recent years, and continues to be made, in improving the defect density of commercially important substrates, crystals, and nonlinear materials. Materials processing and equipment designs need to improve significantly in order to increase the yields on complex micro-optical devices and improve cost-reduction techniques. The technologies outlined in this section include optical systems, equipment, and components. The final area of technologies includes optical countermeasures, which are needed for many military applications on and off the battlefield.

A key technical challenge for optical design and fabrication of miniaturized components is the ability to integrate everything from the design phase through the fabrication phase, with testing and assembly methods that include assembling active optical components into fully integrated optical systems required for miniaturization and improved performance in future products. Some of the other key technical challenges of optics and optical components include cost-effective manufacturing of general aspherics and conformal components; development of VUV optics for microlithography to permit the continued reduction of feature size and enlargement of chip area; low-cost, low-volume, surge-capable optical manufacturing processes which are essential to maintain efficiency and support the continued development of military optical systems; and integrated design, fabrication, assembly, and test methods, which permit the smooth advance of the hybrid micro-optical devices of today into the fully integrated optical systems required for miniaturization and high performance required in future products. In addition, there are some issues that cut across the diversity of optics development and manufacturing process technologies. These include improvement of optical designs and in situ optical polishing using increased computer power, which can provide real-time feedback, and advances in optical metrology, which provide the wherewithal to “measure what you make” in these small micro-optics components.

Some specific military requirements will be addressed by technologies outlined in this section. These include long-range chemical detection using light detection and ranging (LIDAR) or other stand-off techniques to give tactical advantage, an effective detection and identification system for various mission requirements, a method to determine ultra-low species concentration detection, lightweight space optics, and high-sensitivity hyperspectral surveillance imaging systems. Optics manufacturing technology, especially that of aspherics and nonconformal optics, is also a major concern to the military. Those developing technologies are covered in this subsection as well.

RATIONALE

Throughout history, new technology has had a profound effect on the conduct and outcomes of wars. Almost without exception, the victor possessed and applied technology not previously seen or used. Nowhere was this more evident than in Operation Desert Storm. During Desert Storm, the accuracy demonstrated by laser- and optics-guided munitions, space surveillance capabilities in near real-time, and the realization that night-vision optics gave the allies “control of the night” pointed out the necessity of maintaining our technological advantage by developing improved military optics and electro-optics systems. The military has a number of efforts under way to improve current capabilities. These include reliance on speed and stealth; detection and control of nuclear, chemical, and biological threats; and real-time information dissemination. Optics will play a key enabling role in all of these efforts. As the recently published National Research Council (NRC) report entitled “Harnessing Light: Optical Science and Engineering for the 21st Century” states, “For the future, optical systems are sure to be the basis for entirely new classes of defense applications that will change yet again the way wars are conducted.”

In its November 1998 report entitled “A Space Roadmap for the 21st Century Aerospace Force,” the Air Force Science Advisory Board stated that research and technology funds should be allocated for military-unique technology needs not likely to be met by commercial sources, identifying and pursuing opportunities to insert technologies in commercial and military applications, and maintaining longer term high-risk/high-payoff technologies where commercial companies cannot justify investing. The report goes on to say that DoD should focus on critical technology needs (e.g., low-cost, lightweight space optics). To a remarkable degree, the cost of all competing concepts of directed-energy in space is driven by the optics required on orbit. DoD requires both primary warning and tracking of objects in high orbits. Advances in both optics and optical materials are needed to accomplish these missions.

Use of optics and optical systems, which improves current manufacturing capabilities and enable new ones, is revolutionizing modern manufacturing in the commercial and military sectors. Light is being used to process and probe materials. For example, it is used remotely, through windows that separate the optics from a harsh environment or vacuum, to evaporate coating material in a vacuum chamber or weld. On assembly lines, optics and lasers are used to scan large surfaces while comparing minute details at phenomenal speeds. Numerous optical techniques critical to the manufacture of products such as semiconductor chips and car bodies are used throughout industry. Technologies that make large space and airborne optics lighter, quicker, and less expensive, both for high-fluence optical weapons applications and for sensor systems that utilize low optical fluences, would benefit virtually any military and some commercial optical systems. These improvements from enabling optics technologies will provide the next-generation field officer with a near-real-time visualization of the battle scene via space communications and remote UAV surveillance. The optics, optical materials, and optical countermeasures outlined in this section were chosen with those concerns in mind.

WORLDWIDE TECHNOLGY ASSESSMENT

The world has experienced a major technological push in many areas in recent years, but especially in optics and electro-optics. Optics, combined with micro-electronics, has seen overnight advances. Numerous international technical conferences now have sections devoted to micro-optics-electromechanical systems (MOEMS), where optics and electronics are combined in what have typically been MEMS or just electronic chip processor components. Advanced process technology for optics, micro-optics, and optical components has changed the way we think about manufacturing optical systems. Many European countries and Asian countries also have participated in this resurgence in optics as an enabling technology for many applications. These advanced manufacturing process technologies are now present in varying degrees throughout the entire industrialized world.

In general, the United States has a significant lead in militarily critical optical systems, components, materials, and optical countermeasures technologies. However, many of our allies (including Israel) are more advanced in some specific areas. Russia and China are more advanced in other specific areas, such as NLO and crystal-growing technology. A number of other countries have one or more niche technologies which are of military significance. Manufacture of mass-market optics components and some optical materials is now dominated by companies in Asia and the Pacific Rim, but some recent developments are enabling U.S. industry to recapture selected market segments. As the NRC report points out, one example of U.S. emergence is the recent development of a new class of numerically controlled optical grinding and polishing machines. Another example is improved understanding (and data base) of the characteristics of optical materials, from glasses to polymers to metals, thus permitting broader use of these automated technologies. Some of these key optical manufacturing process technologies are required to provide affordability for one-of-a-kind or limited numbers of specific military components or systems. A key strength of the U.S. optics industry is its computer-aided optical design capability, which has been revolutionized by the development of fast and affordable ray-tracing software. This strength is currently being threatened by some of the Asian nations as a result of improved capabilities in computer software and the proliferation of high-processor-speed computers.

Country	Sec. 11.2 Optics
Australia	●
Canada	●
China	●●
France	●
Germany	●●●
Israel	●
Italy	●
Japan	●●
Norway	●
Russia	●●
Singapore	●
South Korea	●
Sweden	●
Switzerland	●
Taiwan	●
Ukraine	●
UK	●
United States	●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Figure 11.2-1. Optics Technology Systems WTA Summary

LIST OF TECHNOLOGY DATASHEETS
III-11.2. OPTICS

DATA SHEET III-11.2. PRECISION CONFORMAL OPTICS

Developing Critical Technology Parameter	An ongoing effort is to develop the optical system design, fabrication, and testing capabilities to produce precision conformal optical missile domes for military applications requiring aerodynamically shaped windows on the missile. This technology requires nonrotationally symmetric optical domes. The goal is fine grinding and polishing of nonrotationally symmetric aspheric missile dome surfaces.
Critical Materials	None.
Unique Test, Production, Inspection Equipment	Unique profilometer designs and interferometer configurations appropriate for steep aspheric surfaces and wavefronts will need to be developed. A new polishing technique called "rock and roll" polishing, based on a loose abrasive/slurry approach, is also being studied.
Unique Software	Software will be part of the developed metrology instruments.
Technical Issues	The primary metrology issue relates to the degree of asphericity present on the surfaces. Too many interferometric fringes are present to test conventionally. Null lenses can be used, but are expensive. New metrology techniques are needed to enable the use of aspheric surfaces in many optical systems. Develop the rock and roll polishing technique to provide the necessary surface figure.
Major Commercial Applications	Illumination systems, scanners, microlithography.
Affordability	The rock and roll polishing technique is relatively inexpensive if it can be perfected for this application.

RATIONALE

There is a significant loss of missiles due to overheating of the missile dome during high Mach flights. Sometimes the missile dome cracks under the high thermal gradients produced by the friction of flight. Current domes are predominantly hemispherical in shape. If a cone is used, the drag would be reduced by a factor of 2 or more; however, the optics behind the dome must "see" though the dome, requiring a "window" of some type. This has resulted in a hemispherical dome being the choice over the years. Modern technology permits exploration of nonconventional shapes such as fast aspheric domes, which approach the shape of a cone. These shapes have been modeled, showing the following attributes:

- As much as 50 percent of the drag of a missile is due to the hemispherical nose dome.
- A conformal dome will reduce this aerodynamic drag significantly, reducing the heating effect.
- An aspheric conformal dome will provide additional operational speed or range for the missile.

CaF and sapphire are two of the primary conformal dome materials of interest. Missiles equipped with conformal domes will fly faster and further than current spherical domes. Potential candidates for this technology include the Stinger, Hellfire, and Javelin missiles.

WORLDWIDE TECHOLOGY ASSESSMENT

Canada	●	China	●●	Czech Republic	●	France	●
Germany	●●	Israel	●	Japan	●	Russia	●●
Singapore	●	South Korea	●	Taiwan	●	UK	●●
United States	●●●●						

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

In the United States, the Precision Conformal Optics Technology (PCOT) consortium comprises DARPA, Boeing, Rochester Photonics Corp., Sinclair Optics, University of Arizona/Optics Sciences Center (UA/OSC), U.S. Army MRDEXC, Raytheon, and the University of Rochester/Center for Optics Manufacturing.

The U.S. Air Force and Navy have done considerable research on the development of this technology. There is U.S. Army funding of this effort as well. Currently, Raytheon Corporation’s Tucson Missile Division is actively working on a Navy manufacturing technology program aimed at developing a strengthened dome material and reshaping the dome in a conformal configuration to decrease the resistance and thereby the heating of the missile dome. Other U.S. firms developing this technology include the other PCOT consortium members: Boeing, Rochester Photonics Corp., Sinclair Optics, Optical Research Associates, and Morton CVD.

The Center for Optics Manufacturing, at the University of Rochester in Rochester, New York, is developing computer-controlled grinding and polishing technology to support this effort along with the Optical Sciences Center at the University of Arizona. Their major programs are called advanced Anti-Radiation Guidance Demonstration/ High-speed Anti-radar Missile (AAGD/HARM) and Low-Cost Precision Kill (LCPK). The Center currently has 14 Government, Service, and industry support programs that include conformal optics research as part of their effort.

At this time, there is limited knowledge of research in other countries, but Germany, UK, and Russia are known to be doing research in this area, and China has the capability to develop solutions to this technology issue.

DATA SHEET III-11.2. MICRO-OPTICAL ELEMENTS (MOEs) ON MICRO-OPTICAL TABLE SYSTEMS (MOTS)

Developing Critical Technology Parameter	Tight tolerances are required for optoelectronic components such as micro-lenses and micro-beamsplitters. Position tolerances of less than 1 mrad are required but currently exceed 10 mrad in some applications. Positioning placement errors are extremely tight in some applications such as lenses and gratings, where positioning tolerances of less than 1 µm are required.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Technical Issues	The microchip substrates must allow rounding of corners to make protrusions deeper. Optical elements need to be patterned in a hybrid sol-gel glass in situ.
Major Commercial Applications	Many MEMS technologies have appeared in products. Similarly, MOTS technologies will emerge in the optoelectronics industry products.
Affordability	It is anticipated that major cost savings can be achieved by this technology.

RATIONALE

The field of micro-optical and microelectro-optical device technology is growing exponentially. There are many applications for such technology, from cell phones to missile guidance systems. MOTS will replace many macro-system components in the future. The DOE laboratories and especially Sandia National Laboratory have extensive research in this technology area. Sandia Laboratory plans on spending $300 million over the next few years on the Microsystems and Engineering Science Applications (MESA) facility. "Virtual reality and micro-machines would be wed at MESA, with the aim of making both weapons and commercial products," says Paul McWorter, spokesperson for SNL. This technology incorporates new structures on chips, enabling new functionality. In this way, the plan is to make chips that not only think, but can sense, act, and communicate.

WORLDWIDE TECHNOLGY ASSESSMENT

China	●	France	●	Germany	●●	Japan	●●
Russia	●	Singapore	●	South Korea	●	Taiwan	●
UK	●●	United States	●●●●				

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

In the United States, the DOE laboratories and especially Sandia National Laboratory have extensive research in this technology area. This technology incorporates new structures on chips, enabling new functionality.

Currently, a number of U.S. universities, including the University of Rochester and the University of Arizona, are working on specific technologies in the MOEs, MOEMS, and MOTS fields. U.S. industry partners include Adaptive Optics Associates, ADE Phase Shift, Alcatel Vacuum Technology, Dynamics Research Corp., Labtek, Newport Corp., SpectroLab Analytical, and West Coast Research. One U.S. firm, Potomac Photonics, Inc., has expanded its product line to provide complete microcomponent fabrication such as electroforming, micromolding, and micromachining, using various lasers to form the 2– and 3–D features as small as a few microns.

Leica Microsystems Corp. in Germany is working in this technology area, as is Exitech, Ltd., in Oxford, UK. In Mainz, Germany, researchers held the Third International Conference on Micro Opto Electro Mechanical

Systems. The Institut für Mikrotechnik Mainz, GmbH, has taken a lead role in developing this technology. In addition, Limo-Lissotschenko Mikrooptik, GmbH, Germany, has published a brochure highlighting its micro-optical components, which include microlenses, collimation lens arrays, and beam transformation optics on hybrid optical chips.

DATA SHEET III-11.2. SUBWAVELENGTH STRUCTURED (SWS) SURFACES

Developing Critical Technology Parameter	SWS surfaces can replace multilayer dielectric coating for antireflection, narrowband filters, polarization components, and graded phase plates. This technology uses etching of the substrate surface to produce the physical equivalent of these multilayer coatings. The SWS process uses surface structure (small compared to the illumination wavelength) to synthesize an effective index of refraction. The critical parameters include uniformity (to 10 percent of the wavelength) of the etch channel widths and profile and process technology to provide uniform (to 10 percent of the wavelength) periodic embedded regions within the substrate.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Technical Issues	Producing the desired profile to fractions of the desired wavelength of light while holding tight tolerances in terms of shape, straightness, etc.
Major Commercial Applications	Narrow-band filters for spectroscopic applications, polarization control in auto windshields, and beam-steering components for store checkout scanners.
Affordability	Much more affordable than current multilayer dielectric technology, once the process parameters are achieved.

RATIONALE

The military utility for this technology is quite extensive. Uses range from battlefield optics, scopes, night-vision equipment, and laser rangefinders to polarizers for field glasses and narrow-band filters when lasers are being deployed. The technology uses the principle that the effective index of refraction (n_{eff}) of the surface can be synthesized by varying the duty cycle of the etched profile on the substrate. The advantages over thin films are the following: (1) an ideal quarter-wave surface can be designed; (2) there are no material cohesion problems; (3) there are fewer fabrication steps; and (4) there are less stringent material constraints.

WORLDWIDE TECHNOLOGY ASSESSMENT

Canada	●	China	●	France	●	Germany	●
Israel	●	Japan	●●	North Korea	●	Russia	●
Singapore	●	Syria	●	Taiwan	●	UK	●
United States	●●●						

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The only known research in this technology area is the work at University of Rochester Institute of Optics and at the Rochester Photonics Corporation, Rochester, New York. There is some technology in this area that is currently surfacing at conferences out of Japan but nothing has been published to date. A number of countries identified above are known to possess the basic understanding of the technology involved, but no known research is underway at this time anywhere else.

DATA SHEET III-11.2. GLASS PHOTOSENSITIVITY TECHNOLOGY

Developing Critical Technology Parameter	Ultraviolet photosensitive glass produces positive index of refraction changes with increasing intensity of irradiation. Volume holograms can be formed in bulk Ge-doped silica. The sol-gel technology can produce photosensitive glass.
Critical Materials	Synthesizing high-quality germanosilicate glasses using the sol-gel growth method.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Technical Issues	None identified.
Major Commercial Applications	Photosensitive glass can be used in applications ranging from control of optical parameters to providing 3–D hologram storage of optical information. Very long fiber Bragg gratings can be formed to provide dispersion manipulation for optical communications as well as optical pulse synthesis. Phase gratings in optical fibers are used for controlling reflection and allowing unique control over both the amplitude (pulse shaping) and phase (dispersion) of optical signals.
Affordability	Demonstration of the capability to make large quantities of high-quality, low-cost, photosensitive glass using the sol-gel technique will establish the cost savings.

RATIONALE

The practical implementation of applications like holographic optical data storage is limited by inadequate optical materials. Organic polymers possess many of the required qualities, such as high photosensitivity, but due to density changes upon writing, holographic images degrade when multiple holograms are multiplexed. New approaches maintain the high photosensitivity of existing polymer materials that results from quantum amplification (one photon induces many reactions) but exhibits little or no density change. One new approach is based on isomerization of a high concentration of reactant molecules that are dispersed in a rigid polymer matrix.

Ultraviolet photosensitivity and synthesis in bulk germanosilicate glasses have proven to be a good 3–D holographic storage technique. Glass has low loss, high homogeneity, low birefringence, and excellent mechanical properties. The nonzero photosensitivity of glass needs to be studied to extend its range of applications.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●	China	●●	France	●●	Germany	●●
Israel	●	Japan	●●●	Norway	●	Russia	●●●
Singapore	●	South Korea	●	Sweden	●	Taiwan	●
Ukraine	●	UK	●●	United States	●●●		

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

This technology is rather new and limited in funding. Russia and Japan are developing capabilities for photosensitive glass fabrication. A number of co-inventors of this technology work at the State Optical Institute in Russia. They can bring this technology to a commercial level if the Russian Government funds the corresponding program.

The recent publication of a Japanese research group (K. Miura, J. Qiu, H. Inouye, T. Mitsuyu, K. Hirao) published "Photowritten Optical Waveguides in Various Glasses with Ultrashort Pulses," which shows that they created these photosensitive glasses but still cannot overcome the problem of spontaneous crystallization. If professional glass developers in Japan will be involved in the program, they can improve glass composition and technology after several months of efforts.

A group of researchers led by V.I. Smirnov and O.M. Efimov have written numerous publications, including (1) “High-Efficiency Bragg Gratings in Photothermorefractive Glass,” by O.M. Efimov, L.B. Glebov, L.N. Glebova, K.C. Richardson, and V.I. Smirnov, *Appl. Optics, Optical Technology and Biomedical Optics (OT&BO),* 38, 619–627, 1999; (2) “Polychromatic Glasses—A New Material for Recording Volume Phase Holograms,” by L.B. Glebov, N.V. Nikonorov, E.I. Panysheva, G.T. Petrovskii, V.V. Savvin, I.V. Tunimanova, and V.A. Tsekhomskii, *Sov. Phys. Dokl.,* 35, 878, 1990; and (3) “Photowritten Optical Waveguides in Various Glasses with Ultrashort Pulses,” by K. Miura, J. Qiu, H. Inouye, T. Mitsuyu, K. Hirao.

It is necessary to establish a serious R&D program in the United States to gain affordability of new holographic material and create access to this new photosensitive optical glass technology. It appears that the United States is on an equal footing with Japan and Russia but needs to accelerate this important technology. The Center for Research and Education in Optics and Lasers at the University of Central Florida (CREOL/UCF) and UA/OSC are two university centers currently working on this technology.

DATA SHEET III-11.2. OPTICAL METROLOGY (ASPHERIC SURFACES)

Developing Critical Technology Parameter	The precision measurement of aspheric optical elements is an expensive task, yet aspherics are often the key to the design of simpler, lighter, and less expensive optical systems. Surface testing techniques that do not require the use of null lens elements yet provide high precision are therefore important. The combination of multiple wavelength interferometry using sub-Nyquist sampling and deterministic fringe imaging offers a promising solution, but is still in the research and development stage. Critical technology parameters: Dynamic range (1E5), and P–V accuracy (< 5 nm).
Critical Materials	Stable laser sources and megapixel image sensors.
Unique Test, Production, Inspection Equipment	Aspheric optical element testing can be improved significantly with the use of multiple-wavelength interferometry combined with deterministic fringe imaging. This technology needs to be developed.
Unique Software	High-speed acquisition/processing of digital images.
Technical Issues	Alignment tolerances and corrective ability at high dynamic range.
Major Commercial Applications	Aspheric optics for displays, video cameras, medical imaging, and projection lithography.
Affordability	Currently there are no commercial systems that will provide the necessary dynamic range.

RATIONALE

The use of aspheric optics offers weight and cost reduction and provides for flexible designs in the context, for example, of conformal optics (in which a front surface must conform to a nonoptical specification). An interferometric test for a single aspheric surface can cost upward of $25,000. Thus, both military optics and consumer optics would benefit from a method of non-null testing of aspheres.

The optics community has long required a cost-effective technique to measure the accuracy of aspheric surfaces. There is no significant effort in any country to solve this problem. Null lenses are difficult to design and also difficult to test. Once a null lens is fabricated, it is almost as difficult to test as the aspheric it was designed to measure. Therefore, this technology is the best practical solution to this problem.

WORLDWIDE TECHNOLOGY ASSESSMENT

Canada	●	China	●●	France	●	Germany	●●●
Japan	●●	Russia	●	Sweden	●	Switzerland	●
Taiwan	●	UK	●●	United States	●●●		

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

There are few researchers in any country working on solutions to this testing issue. The United States and Germany are actively trying to solve this problem in a cost-effective and time-efficient manner. Thomas Brown at the University of Rochester/Institute of Optics is actively working to solve this by the technology outlines above. No other significant foreign efforts are currently known.

DATA SHEET III-11.2. HOLOGRAPHIC OPTICAL ELEMENTS IN PHOTO-THERMO-REFRACTIVE GLASS

<table>
<tr>
<td>Developing Critical Technology Parameter</td>
<td>
Holographic optical element (HOE) fabrication is a rapidly developing technology because of great advantages in decreasing of weight and sizes of laser-based optical systems. A volume HOE in a durable inorganic photo-thermo-refractive (PTR) glass with diffraction efficiency of 40 percent originally was developed by State Optical Institute, St. Petersburg, Russia. This technology was significantly improved at CREOL/UCF and resulted in diffraction efficiency increasing up to 95 percent. PTR/HOE have thermal, chemical, and mechanical properties of routine multi-component silicate glasses; are tolerable to IR, visible, and UV radiation; can be designed for transmitting and reflecting configurations; and a number of components can be superposed in the same element.
By 2010, projections indicate dramatic increase of sizes and decrease of losses in UV and middle IR regions. There is expected use of PTR/HOE in commercial markets for high-quality laser systems, optical communications, data storage, and data processing. All these applications are very attractive for military applications because of high thermal stability of PTR/HOEs. The most promising application is for laser radar, specifically for laser beam cleaning, angular beam scanning, and spectral filtering in receivers. Commercially, Light Processing and Technologies, Inc., recently spun off CREOL for research, development, and manufacturing of PTR/HOE.
<table>
<tr><th>Parameter</th><th>1999</th><th>Projected by 2010</th></tr>
<tr><td>Spectra range of photosensitivity (nm)</td><td>280–370</td><td>280–800</td></tr>
<tr><td>Spectra range of operation (nm)</td><td>300–1100</td><td>250–4000</td></tr>
<tr><td>Diameter (mm)</td><td>5</td><td>250</td></tr>
<tr><td>Thickness (mm)</td><td>2</td><td>20</td></tr>
<tr><td>Spectra selectivity at 633 nm (FWHM, pm)</td><td>700</td><td>50</td></tr>
<tr><td>Angular selectivity at 633 nm (few^{-1}, mrad)</td><td>0.5</td><td>0.02</td></tr>
<tr><td>Diffraction efficiency at $\lambda > 400$ nm (%)</td><td>90–95</td><td>95–99</td></tr>
<tr><td>Diffraction efficiency at $\lambda < 400$ nm (%)</td><td>10–12</td><td>50–70</td></tr>
</table>
A number of R&D efforts are directed to the development of higher quality PTR glasses (optical homogeneity, homogeneity of sensitivity, shift of photosensitivity to the visible and IR regions) to study of features of diffraction process in super thick holograms.
</td>
</tr>
<tr>
<td>Critical Materials</td>
<td>PTR glass, which is sodium-zinc-aluminum-silicate glass doped with silver, cerium, and fluorine. The single glass melting facility specialized in PTR glass fabrication is at CREOL/UCF. The glass can be fabricated at conventional optical glass melting facilities.</td>
</tr>
<tr>
<td>Unique Test, Production, Inspection Equipment</td>
<td>High-quality hologram writing facility is necessary for PTR/HOE writing with UV laser. Power requirements are about 10 mW/cm^2.</td>
</tr>
<tr>
<td>Unique Software</td>
<td>Commercial software is available for glass fabrication and PTR/HOE design and fabrication.</td>
</tr>
</table>

Technical Issues	Development of PTR glass fabrication technology which enables homogeneity of refractive index and photosensitivity at large diameters, development of hologram writing, and development of technology which enables homogeneity of diffraction efficiency and spectral and angular selectivity for high-power laser applications. These issues are to be solved in the development process of powerful laser systems design for military applications. Basic skills for R&D, design, and fabrication are the combination of conventional skills for optical and optical materials industries. Specific glass with volatile components and recording processes in the UV region require some additional skills for technical personnel. The commercial technology of PTR/HOEs does not require further development for military applications except to meet specific requirements for larger sizes for high-power laser systems.
Major Commercial Applications	The main commercial applications of PTR/HOEs are spectral and angular filtering for optical communications, spectroradiometers, and spectral analysis, laser-beam steering; mode selection in lasers; and attenuation and splitting of collimated beams. PTR/HOEs will be drivers of new design because of potential low cost, feasibility of large-scale manufacturing, environmental stability, and high optical merits.
Affordability	Not an issue.

RATIONALE

Volume holographic optical elements in PTR/HOEs may provide unique merits for optical systems as narrow-band spectral filters, angular selectors, and beam deflectors. Compared to the conventional optical elements, they decrease weight and size of optical components. Compared to known HOEs fabricated from dichromated gelatin or lithium niobate, they increase thermal stability and lifetime. These features are most attractive for laser systems on aircraft- or space-based platforms.

Potential military applications are such components of laser radar as mode selectors, beam deflectors and spectral filters, selective mirrors in telescopes directed to provide images in the narrow spectral region (including UV), and spectral filters in WDM for optical communications. A number of such applications are of high importance for new DoD programs:

- *Detection of signals or images in narrow spectral lines (air- and space-based telescopes and radiometers, laser radars, range finders, etc.).* Maximal signal-to-noise ratio (SNR) of a receiving optical system operating under conditions of strong external illumination (enemy's lasers, radiation of explosions, etc.) is reached when the spectral width of a receiver is about of the spectral width of a signal. An interference filter is one of the conventional systems used for spectral selection in receivers; however, the interference filters allow selection of spectral regions of 1 or more nanometers with transmission below 50 percent [see, e.g., Refs. 1 and 2)], although the spectral line width of laser radiation can be hundreds of times smaller. A more promising way to detect narrow-band radiation is the use of a volume Bragg grating because a higher spectral selection can be achieved (Refs. 3, 4). There are a number of materials applied for volume Bragg recording, but none meets all requirements for a reliable holographic material (Ref. 5). The proposed approach is based on recent success at CREOL/UCF in a study of hologram recording in photosensitive inorganic glasses (Ref. 6), which was supported by BMDO contracts for the last 3 years (Contracts N6600197C6008 and N6600198D6003). Formation of Bragg grating in PTR glass is a result of a two-step process including an exposure to UV radiation followed by thermal development. This medium allows high-diffraction efficiency of transmitting Bragg gratings; excellent response at high spatial frequencies; and perfect thermal, optical, and mechanical stability. A patent application—"Photo-thermo-refractive optical elements and methods"—on behalf of the University of Central Florida was recently submitted. Thus, PTR reflectors in telescopes, radiometers, laser radars, and range finders enable a design of new generation of narrow-band receivers in target and background tracing.
- *Laser-beam deflection, splitting, and attenuation (scanning and beam shaping systems in laser radars and range finders, e.g., STAB program at DARPA).* Low losses, high diffraction efficiency, low sensitivity to

polarization, and sharp angular dependence of diffraction efficiency of gratings allow fine gradual attenuation with the uniform attenuation in diameter and simultaneous beam cleaning like a spatial filter. The feature of Bragg grating to split a beam to components with the same polarizations allows beam splitting with stepless ratio of intensities. Finally, this approach can give an arbitrary number of beams with arbitrary desirable intensities and the same polarization. It is clear that the grating rocking can produce a variable splitting ratio or scanning system. Scanning rate in configuration of the regular compact disc can be up to 10 kHz for a 3-mm diameter beam. The use of Bragg gratings in PTR glasses allows a development of several designs, which can overcome some problems, usually encountered in electro-optical and acousto-optical modulators (small angular deflection). The combination of traditional scanning with a matrix of holograms allows realization of a high scanning rate and wide angular deflection. Recording of multiple gratings in the same volume, readable under different angles, allows switching between different regimes by rocking the matrix. Thus, PTR deflectors, attenuators, and beam splitters in air- and space-based laser systems can significantly decrease the size and weight of systems, while improving beam quality.

- *Selection of transversal and longitudinal modes in laser cavity to enable single-mode operation (laser radars, range finders, aims, etc.).* Application of laser radiation for target recognition or for range finding requires a very high quality of laser beams. Mostly, it should be a single-mode operation to secure a diffractive limit of divergency and narrow spectral line. The main conventional methods of transverse mode selection are based on spatial filtering using different spatial mode distribution in a laser cavity (Ref. 7). However, it is clear from Reference 7 that the main difference between transverse modes of different orders is in their angular distributions. In this case, angular selection by volume diffractive gratings looks more beneficial. The first promising results of angular mode selection were shown in Reference 8. What mainly restrains an application of diffractive elements is the lack of reliable materials for Bragg grating fabrication (Refs. 3–5, 8). Thus, the use of PTR mode selectors in resonators of portable high-power laser systems will increase both power and beam quality while overall dimensions and weight will be decreased.

WORLDWIDE TECHNOLOGY ASSESSMENT

Japan	●●●	Russia	●●●	United States	●●●●

Legend: Extensive R&D	●●●●	Significant R&D	●●●	Moderate R&D	●●	Limited R&D	●

In the United States, technologies of PTR glass fabrication and volume diffractive gratings recording are established at CREOL/UCF. Light Processing and Technologies, Inc., is working on commercialization of PTR/HOE. A lot of research efforts all over the world are directed to creation of reliable HOEs.

No special cooperative agreements concern PTR holographic elements. Russia and Japan can easily develop capabilities for PTR glass fabrication and HOE creation. A number of co-inventors of PTR technology of holographic element fabrication (Refs. 9, 10) still work at State Optical Institute in Russia. They can move this technology to commercial level if the Russian government funds the corresponding program. The recent publication of a Japanese research group (Ref. 11) shows that they created PTR-like photosensitive glass but still cannot overcome the problem of spontaneous crystallization. If professional glass developers in Japan will be involved in the program, they can improve glass composition and technology after several months of efforts. It is necessary to establish additional serious R&D programs in the United States to gain affordability of new holographic material and create access to new holographic optical elements.

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SECTION 11.3—OPTICAL MATERIALS AND PROCESSES

Highlights

- Optical materials protect sensors in hazardous atmospheric conditions while still allowing signals to pass.
- Optical coatings are used to
  - Reduce scatter and reflection by gradually modifying the index of refraction along an optical path,
  - Selectively filter incoming radiation to the sensor, and
  - Protect optical elements.
- Nonlinear optical (NLO) materials are used to shift the wavelengths (or frequency) of radiation to more desirable levels.
- Optical materials, including laser-diode-pumped fibers, are used to transfer information faster and at higher bandwidth than electrical wires.
- Optical materials are used for protection against unwanted radiation.
- Optical materials are used as a medium for lasing.
- Many optical processes that cut grinding and polishing time by an order of magnitude are being developed.
- Optical processing can now occur on the chip, which allows optical processing and computing information to be considered in many new and revolutionary ways.

OVERVIEW

This section includes optical materials, optical material technologies for linear and nonlinear materials with transmission in the visible and/or IR spectral regimes, and optical processing. This subitem includes both bulk materials and thin films and coatings. Depending on the application, these materials/coatings may be required for either broad- or narrow-band applications. Special emphasis is placed on materials and coatings which are affordable, maintainable, and durable in harsh environments experienced in military operations, such as exposure to high-energy lasers, high temperatures, or high structural loads associated with high-speed, maneuvering flight. This section includes optical materials for (1) high strength, multispectral optical applications; (2) supersonic IR window/domes; (3) multifunction IR coating materials; (4) specialty transparent materials for optical coatings and filters; (5) NLO materials for wavelength conversion; and (6) photonic crystals which can be used to control light switching and directional flow of light. Optical processing is covered as it relates to new, innovative technology for computer-controlled optical grinding and polishing, as well as new and revolutionary processing of optical components on chip-level components.

In most cases, the mission requirements of individual weapons platforms and their associated optical systems dictate the specific capability of the optical materials and coatings in the components thereof. Capability not only refers to the accuracy of the system or sensor component, but it also includes durability, availability, and cost of ownership.

Many factors involving electro-optical countermeasures are peculiar to the military. As an exception, some of the nonlinear optical materials will likely be utilized in lasers for detection and identification of chemical species in environmental pollutants, and some forms of the optics coating technology could be adapted by the optical industry for commercial aviation of night vision (IR) sensors and other applications.

RATIONALE

The accurate assessment of target location through surveillance and subsequent pinpoint delivery and guidance of missile assets is critically linked to the durability and survival of the optical sensor/seeker systems on board the delivery platform and the munition. Both must endure adverse environmental and hostile conditions, such as rain and dust and electro-optical countermeasures, often at supersonic speeds. These capabilities are provided, in part, by optical materials and/or coatings, and directly determine the delivery accuracy and lethality of manned and unmanned guided weapons systems. Access to materials and coating technology would amplify threats to regional stability to a critical extent by making available to hostile forces a much superior material and/or optical coating/filter for windows, missile domes and optical elements for electro-optical sensor systems capabilities. The current U.S. technology lead translates into a combat and performance advantage for U.S. military forces, and the technologies outlined in this section have the potential to maintain or enhance this advantage.

WORLDWIDE TECHNOLOGY ASSESSMENT

Some of the materials and coatings technologies covered in this subitem are being developed and/or produced in the UK, France, Israel, and Japan, and perhaps in China and the former Soviet Republics.

Country	Sec. 11.3 Optical Materials and Processes
Canada	●
China	●●●
France	●●
Germany	●
Israel	●
Japan	●●●
Malaysia	●
Netherlands	●
Norway	●
Russia	●
Singapore	●●
South Korea	●●
Sweden	●
Switzerland	●
Taiwan	●●
Ukraine	●
UK	●●
United States	●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Figure 11.3-1. Optical Materials and Processes Systems WTA Summary

LIST OF TECHNOLOGY DATASHEETS
III-11.3. OPTICAL MATERIALS AND PROCESSES

DATA SHEET III-11.3. NONLINEAR MATERIAL DEVELOPMENT FOR THE 3.5-µm WAVELENGTH REGION

Developing Critical Technology Parameter	Nonlinear materials for frequency conversion at the important 3.5-µm wavelength region, where hydrocarbon molecules absorb and can be detected in the atmosphere. Nonlinear crystals must meet the physical requirements of a large nonlinear coefficient, have good optical quality, be chemically stable, easily grown, and easily fabricated into optical components and devices.
Critical Materials	Inexpensive tunable parametric oscillator (NLO) materials.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Technical Issues	Lithographic planar processing is required for mass-producing nonlinear crystal "chips."
Major Commercial Applications	Air pollution monitoring.
Affordability	Since thousands of chips of lithium niobate can be produced on a 4-in. diameter wafer, the cost could be reduced to a few dollars per chip.

RATIONALE

Recently, nonlinear materials manufacturing technology has led to the use of lithographic process technology to apply various materials to silicon wafers. This technology could reduce the cost by factors of 10 to 100, possibly by 1,000 or more. If lithium niobate can be applied to this lithographic planar processing technology, it would be possible to fabricate nonlinear chips for both commercial and military applications. The nonlinear effects, such as conversion efficiency, can be optimized by using spatial modulation of the ferroelectric domains to achieve quasi-phase matching. This would permit wavelength selection into appropriate absorption bands.

Lithographic planar processing techniques for mass production of silicon integrated circuits is a possible solution. Lithium niobate is a prime candidate material.

WORLDWIDE TECHNOLOGY ASSESSMENT

Canada	●	China	●●●	France	●	Germany	●
India	●	Israel	●●	Japan	●	Netherlands	●
Russia	●●	Singapore	●	Switzerland	●	Taiwan	●
Ukraine	●	UK	●	United States	●●		

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

China has the lead in this technology with significant R&D effort, followed closely the United States, Israel, and Russia.

DATA SHEET III-11.3. SOL-GEL WAVEGUIDES FOR INTEGRATED OPTICS

Developing Critical Technology Parameter	The development of sol-gel waveguides and Bragg gratings for use with integrated optics is needed to provide low-loss optical components and feedback resonator gratings for on-chip applications. This technology will provide a simple, low-cost approach to heterogeneous integration of optoelectronics, multiwavelength lasers with optimized linewidth, and a wide range of integrated optical components on integrated chips. The sol-gel technology needs very low-loss materials to make this technology feasible.
Critical Materials	High-purity sol-gel materials with very low optical attenuation and absorption loss.
Unique Test, Production, Inspection Equipment	Packaging and reliability testing under harsh environment. Testing to less than 0.05-percent absorption is required.
Unique Software	Capable, fast, and accurate design tool for heterogeneous integration.
Technical Issues	Improved reliability and reproducibility for large-volume production.
Major Commercial Applications	The technology will provide for the transmission of different wavelengths in parallel, which will increase the transmission capacity, and allow simultaneous transmission of different signal modes (voice, data, image, etc.). The immediate applications are for optical networks and supercomputer links.
Affordability	This technology not only will significantly reduce the cost of service but will provide a component that does not exist in the current optoelectronic technology inventory.

RATIONALE

The Bragg grating sol-gel technology will open a wide choice of applications in the optoelectronics area. Low-cost multiwavelength sources, wavelength filters, and splitters are key components for advanced optical systems. This technology will provide a low-cost addition to current technology in this area and significantly increase the possibilities for optical links. Combining sol-gel and semiconductor technology will provide a new dimension to the heterogeneous integration of optoelectronic components. The technology will provide new chip-scale high-performance, low-cost modules for terabit optical links and RF-lightwave transmission systems for radar, navigation, and communication.

WORLDWIDE TECHNOLOGY ASSESSMENT

Canada	●●	China	●	France	●●●	Germany	●●●
Italy	●●	Japan	●●●	Spain	●	Sweden	●●
UK	●●●	United States	●●●				

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The United States, Japan, UK, France, and Germany have the lead in this technology with significant R&D.

DATA SHEET III-11.3. SELF-CHANNELING NLO MATERIALS DEVELOPMENT TECHNOLOGY

Developing Critical Technology Parameter	Generation of spatial solitons (beams of light that propagate long distances without spreading) and light bullets (ultrashort pulses that propagate without spreading in time or space) for applications such as directed-energy delivery and optical logic. Establishment of self-channeling of light waves in air for applications such as the generation of electrically conducting channels. Optical power limiters for sensor protection.
Critical Materials	Need development of new second-order and third-order NLO materials. Need materials with low absorption and high resistance to laser damage. Composite materials offer an attractive means for improving material performance if they can be developed with the properties required.
Unique Test, Production, Inspection Equipment	Materials assessment using self-focusing techniques (such as z-scan). Assessment of the ultrafast dynamics of photonic materials by time resolving the field evolution of an optical pulse.
Unique Software	None identified.
Technical Issues	Generation of light waves with exotic quantum statistical properties (so-called squeezed light fields) for performing noise-free measurements. Unique imaging opportunities using terahertz optical pulses, including imaging through biological materials. Elucidate role of composite structures in optimizing properties of photonic materials. The use of NLO methods for image processing.
Major Commercial Applications	Tunable light sources based on NLO interactions. Photonic switching for optical communications.
Affordability	NLO is intrinsically a low-cost solution once development is complete.

RATIONALE

NLO constitutes the study of the interaction of intense light with material systems. The military utility of this technology includes understanding how targets respond to intense laser radiation, the use of nonlinear techniques for image recognition and low-light-level imaging, the transmission and switching of optical signals in both free-space and fiber-optic environments, the enhancement of sensor characteristics, and the development of optical data-storage devices. These specific attributes are the key reasons that improved NLO materials are needed to provide better visibility at night, better covert communication links, and improved high-bandwidth audio/video for many military applications.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●●●●	Canada	●●●	China	●●	Cuba	●
Czech Republic	●	Egypt	●	France	●●●	Germany	●●●
Hungary	●	India	●●	Iran	●	Iraq	●
Israel	●●●	Italy	●●●	Japan	●●●●	Malaysia	●
Netherlands	●●●	North Korea	●	Norway	●●	Poland	●●
Russia	●●●	Singapore	●	South Korea	●●●	Sweden	●●●
Switzerland	●●	Syria	●	Taiwan	●●	Ukraine	●●
UK	●●●	United States	●●●●				

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Australia, the United States, and Japan have the lead in this technology with extensive R&D, followed by Israel, the Netherlands, Russia, UK, Canada, Italy, France, South Korea, Germany, and Sweden with significant R&D programs. Limited R&D is under way in several other countries.

DATA SHEET III-11.3. ELECTRO-OPTIC AND PHOTOREFRACTIVE NLO POLYMER TECHNOLOGIES

Developing Critical Technology Parameter	With the emergence of electro-optic/photonic technologies in areas such as range finding, data storage, and telecommunications, where information is coded, transported and routed optically, there is a significant technological demand for high-performance NLO materials. The second-order NLO materials exhibit the linear electro-optic effect in which the refractive index of the material can be controlled through the application of an external electric field. A fundamental understanding of the interrelationship between the chemical and NLO properties of these materials is required, and an optimization of parametric effects is necessary to fully utilize the inherent capability of these NLO materials.
Critical Materials	Organic dyes and polymeric organic systems such as stilbenes or diphenyl polyenes.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Technical Issues	A method of producing dye concentrations in electrically poled polymers to achieve a noncentrosymmetric orientation of the molecules with enhanced NLO properties is needed. NLO materials with temporal stability at elevated temperature are required.
Major Commercial Applications	Many commercial applications in the field of telecommunications, data storage, and computing are just a few of the potential applications where optical devices will replace electronic devices.
Affordability	To be determined, but should be significantly more affordable since higher efficiency, higher data rates, and small data storage space is required for the same electrical capability.

RATIONALE

The second-order NLO effects occur only in molecules lacking a center of symmetry. This effect can be used to impress information on an optical carrier signal by modulating its phase or amplitude with an applied field varying in time and in amplitude. Such materials can therefore be used for the fabrication of ultrafast integrated electro-optical modulators. The NLO properties of materials can be used to control the phase, the state of polarization, or the frequency of light beams at very high rates. The method most widely used to impart noncentrosymmetry in noncrystalline systems is the poled-polymer approach. When combined with the photoconducting and photorefracting properties of these materials, this effect can be used to store information optically by spatially modulating the refractive index of a photorefractive material. The photorefractive effect is based on a combination of photoconducting and electro-optic properties, and it can lead to high refractive index variations under the illumination of low-power lasers. Therefore, NLO materials can be used to store and restore information optically or to deflect light beams and thereby route optical information between fiber-optic channels.

The key to this technology is the development of a range of compounds with diverse NLO bulk properties in noncentrosymmetric materials. Some of the newer polymers exhibit additional orientational effects which are largely responsible for the high performance of this new class of materials and have drastically changed the optimization criteria of photorefractive polymers. Photorefractive materials are suitable for recording and storage of optically encoded information. They are also reconfigurable, so the recording of optical information can be performed in real time. Hence, photorefractive materials are not only suitable for optical storage but also show particular promise for real-time optical processing applications. Until recently, the photorefractive effect has been studied mainly in inorganic crystals that are difficult to produce and to process. In contrast, highly efficient photorefractive polymers, such as the plasticized polyvinyl carbazole-based polymers, exhibit an orientational contribution to the refractive-index modulation. This so-called orientational enhancement effect is due to the ability of the chromophores to orient at room temperature under the influence of an electric field, which is the result of the superposition of the internal modulated field and any externally applied field. As a result, in steady state after photorefractive hologram or three-dimensional image formation, the molecules no longer have a uniform orientation but can have an orientation that is spatially modulated both in magnitude and in direction. That periodic orientation of the chromophores doubles the effect of the electro-optic contribution and, more important, leads to a modulated birefringence that significantly enhances the total refractive-index modulation. Hence, there is a strong need for photorefractive polymers with a high "glass" transitional temperatures; in other words, photorefractive polymers that are stable at relatively high temperatures. Such polymers are poled and have stable electro-optic properties. These materials will find "homes" in many applications requiring three-dimensional storage of information.

The Services have a significant need for low-cost, high-data-storage write and rewrite information systems. This NLO photorefractive technology will be a good fit to that need once the development phase is complete.

WORLDWIDE TECHNOLOGY ASSESSMENT

Canada	●	China	●●	France	●	Germany	●
Israel	●	Italy	●	Japan	●	Russia	●
Singapore	●	Taiwan	●	UK	●●	United States	●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The United States has the lead in this technology, followed by UK and China.

DATA SHEET III-11.3. PHOTONIC CRYSTAL TECHNOLOGY

Developing Critical Technology Parameter	Photonic crystals are materials that have a patterned periodicity in their dielectric constant. This periodicity creates forbidden frequency bands called photonic bandgaps. Photons with energies within the bandgaps cannot propagate through the crystal. As a result, this phenomena can be used to control the flow of light for photonic information technology. The main difficulty to date in designing an all-photonic circuit is the lack of optical components analogous to the electronic transistor. Photonic crystals hold the key to continued progress toward an all-optical system. In a semiconductor, the atomic lattice presents a periodic potential to the electron propagating through the electronic crystal material. In a photonic crystal, the periodic potential is due to a lattice of macroscopic dielectric material instead of atoms. In an optical analog of the electronic bandgap in semiconductors, photonic crystals control light flow by the photonic bandgap, and defects within the crystal can be used to manipulate the photons even further. The introduction of a defect in the crystal allows generation of electromagnetic states with specific properties. Therefore, photonic crystals show great promise for controlling the flow of photons in future photonic networks. To this end, it is necessary to develop an understanding of photonic structures on the same level as has been done for electrons in semiconductors and find NLO materials which work analogously to them.
Critical Materials	New photonic crystals and parameter evaluation of same for specific applications.
Unique Test, Production, Inspection Equipment	Advanced microlithography techniques to fabricate the crystal structures. Electron-beam lithography and X-ray lithography are required.
Unique Software	Computer codes to run the crystal-layering process in fabrication.
Technical Issues	Understanding what defects are required for specific properties within the crystal. NLO materials which perform functions analogous to electron transistors are needed. Manufacturing process technology of photonic crystals with inherent dielectric periodicity is needed.
Major Commercial Applications	The commercial applications are numerous, including every conceivable device that currently has an electronic circuit. The most probable use will be in processors and computers where speed and efficiency are required in yet more miniaturized packages with less heat removal.
Affordability	This technology will be much more affordable than that of electronic chip circuits; it will be an order of magnitude smaller in size than today's technology permits because of less heat being generated and thus capable of operating at higher speeds. It will take considerable effort to develop the photonic crystals and parameterize them for various defect concentrations. When this development is complete, the technology should provide a basis for higher efficiency, lower heat removal, higher speed, and longer lasting chip technology.

RATIONALE

Light (i.e., photons) can eliminate the increased resistance and higher levels of power dissipation in electronic chip circuits. Photonic crystals can be used with photons in much the same way that ordinary semiconductor crystals affect the properties of electrons. In the quest for improvement in high-density integration and system performance, scientists are now developing photonic crystal technology for photonic networks.

This technology provides significant improvement in the miniaturization and high-speed performance of integrated electronic circuits. Light can travel at much greater speeds than electrons in circuits. Light can also carry a large amount of information per second. The bandwidth of dielectric materials is orders of magnitude larger that that of metals. Despite the numerous advantages of photons, an all-optical circuit has yet to be commercially available on a mass-produced scale. The difficulty in designing a multipurpose optical component analogous to the electronic transistor has slowed the development of optical circuits. Photonic crystals may hold the key to the continued development of an all-optical system.

WORLDWIDE TECHNOLOGY ASSESSMENT

Canada	●	China	●●●	France	●	Germany	●
Israel	●	Japan	●●	Netherlands	●	Singapore	●
Taiwan	●	UK	●●	United States	●●●		

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

China and the United States have the lead in this technology with significant R&D, followed by Japan and the UK with moderate R&D efforts.

DATA SHEET III-11.3. PLASTIC OPTOELECTRONICS

Developing Critical Technology Parameter	The critical technology parameters center on low-optical-loss materials development. Sources, transmitters in the gigahertz plastic optical fiber (POF) and 100-GHz electro-optical modulation, and electronic drivers in organic or polysilicon are required. Organic light-emitting displays with 20 lm/W and with a minimum of 180,000 cd/m^2 CW operation are needed.
Critical Materials	Low-optical-loss electro-optic polymers, organic photorefractive materials, organic electroluminescent materials, high-cross-section two-photon absorbing materials, and improved electrolytes for Li batteries.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Technical Issues	Better structure/property relationships with improved performance and reliability are required. One key technical issue is the development of a theoretical framework for charge transfer in highly polar multifunctional polymers. In addition, low-cost manufacturing needs to be demonstrated.
Major Commercial Applications	Telecommunications, displays, and security applications are the major areas of interest at this time.
Affordability	Syntheses of molecules and polymers can be achieved at low cost. New environmentally friendly manufacturing as now available in microprinting will improve the cost factor.

RATIONALE

Plastic optoelectronics is a window of opportunity based on recent breakthroughs in organic photonic materials. The telecommunications and display business are an immediate marketplace for this technology. Many applications in military sensors and communication systems will benefit from the reduced weight and cost of these components. Defense applications include correlators for security checking, high-speed modulators in the GHz range, head-mounted displays, organic laser diodes, laser eye and sensor protection, and plastic optoelectronic circuitry.

WORLDWIDE TECHNOLOGY ASSESSMENT

France	●	Japan	●	Russia	●	UK	●
United States	●						

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

There is only limited R&D in plastic optoelectronics activity in France, the United States, Japan, Russia, and the UK.

DATA SHEET III-11.3. COMPUTER-CONTROLLED OPTICAL GRINDING/POLISHING

Developing Critical Technology Parameter	This critical technology addresses new production methods and affordable manufacturing technologies needed to produce the optics required for critical defense optical systems and sensors. Nontraditional computer-controlled optics are needed to significantly reduce costs while increasing the detection range of electro-optical/IR sensors, improving their angle-of-arrival determination, enhancing the probability of detection, and reducing false alarms. Nontraditional optics are unique in that they conform to the reduced-signature mechanical shapes and aerodynamic requirements of the airborne platform on which they are mounted—all while significantly reducing the production costs of these systems. Surface accuracy <0.5 µm and surface microroughness <1 nm rms will be required for visible and multispectral optics. The precision needed to attain these requirements over a large working volume exceeds the capabilities of commercially available machine tools and processes by 2 to 3 orders of magnitude.
Critical Materials	There are no specific critical materials. System materials range across the UV, visible, multispectral, and IR spectrum.
Unique Test, Production, Inspection Equipment	Extend deterministic microgrinding and magnetorheological finishing processes to computer-controlled machining platforms that will produce non-axisymmetric and freeform optical surfaces that conform to the platform shape into which they are mounted. New machining and finishing centers to automate the production of a wide spectrum of refractive and reflective optics in nontraditional shapes are required. Manufacturing tools, methods and practices must be developed to accommodate the affordable production of these complex, freeform optical shapes. Metrology for axisymmetric and nonaxisymmetric shapes is unavailable because of the unique technical requirements and limited market size. Metrology for in-process and final inspection measurements of freeform surfaces is needed.
Unique Software	Computer-aided design (CAD) and system software to support five-axis freeform machine programming, on-machine inspection, and feedback automation are needed. Real-time computing of surface figure via interferometry is still required.
Technical Issues	Situation awareness, fire-control accuracy, and ultimate battlefield control are directly related to the precision of the optics. Improved optics extend system performance and expand the limits of possible target detection, identification, and imaging resolution. Additional challenges include fabricating these shapes in the wide variety of UV, multispectral, and IR materials preferred. Materials for advanced military applications, such as chemical vapor deposition (CVD) diamond, sapphire, and metal matrix composites (MMCs), are among the hardest and most difficult-to-work materials known. Many optical materials have unique anisotropy and/or grain structures that cause significant machining asymmetries. This makes the fabrication of extremely accurate, nontraditional optical shapes very difficult. Current coordinate measurement and profilometry metrology lack the precision and accuracy required to quantify freeform optical surfaces. Optical test methods, including interferometry, are not available for the unique shapes required.
Major Commercial Applications	Military unique applications drive the importance of these technology developments. Commercial requirements for these types of optics will quickly emerge when it is demonstrated that an affordable manufacturing technology is available.

Affordability	The combination of extreme accuracy, unusual shapes, and difficult-to-work materials results in next-generation optical systems that are well beyond current fabrication capabilities—at any affordable cost. The alternative to developing adequate optics manufacturing technology is controversial design workarounds, unsatisfactory performance reductions, and cost penalties for future military systems. Manufacturing technology investments are required to minimize life-cycle costs and achieve affordable no-compromise optical performance for next-generation military systems. Cost reductions of 10× are being achieved for aspheric optics as a result of past DoD manufacturing technology investments.[1,2] Making similar DoD investments that will build on and advance these manufacturing technology developments is the only solution that will achieve the goal of affordable conformal optics.

RATIONALE

This cross-cutting, nontraditional, conformal optics-manufacturing technology is broadly applicable to all military Services and nearly all weapon systems and sensor platforms. Both axisymmetric and nonaxisymmetric conformal shapes in a combination of aspherical, spherical, cylindrical, conical, toroidal, plano, or ogive shapes are required. In some extreme cases, there may be no symmetry to the optical surface at all, a true "freeform" shape. Performance criteria impacted by this parameter include improved detection range, target acquisition, and resolution, which ultimately improve weapon and system performance. Conformal optical shapes provide significant improvements in low observability, reduced signature, aerodynamic flow, weight, and drag reduction.

As next-generation weapon systems evolve, military prime contractors are finding direct conflicts between the requirements for increased optical sensor performance and the requirements for low-observable, lightweight, high-speed systems. Attempting to mitigate these conflicts using traditional optical shapes (spherical lenses, flat windows) results in unacceptable compromises for next-generation systems. Affordable nontraditional optics are needed to meet these new requirements.[3,4,5] Only the development of this unique, cutting-edge optics-manufacturing technology will provide superior combat capabilities to the warfighter.

The battlefield requires threat detection and recognition systems, in combination with optical targeting and guidance systems, that operate in hard-to-distinguish threat environments, in all conditions, day or night. Optics are critical components of surveillance and reconnaissance systems. Since UV, visible, and IR optical systems remain the ultimate solution for these requirements, highly precise optics are pervasive in the military—ranging from the least complex land warrior's night vision system to the far more complex laser range finders, target designators, missile seekers, aircraft threat detectors, and precision-guided munitions required for ultimate battlefield control.

All projections for future military systems indicate that the trend toward higher performance optical solutions will continue to escalate. The *Defense Technology Area Plan*[6] calls for increasing the detection range of electro-optical/infrared sensors by 100 percent; improving their angle-of-arrival determination to better than 1 deg; enhancing the probability of detection to more than 95 percent; and reducing false alarms to less than one per hour—all while reducing the production costs of these systems.

The combination of ultraprecise surface shapes and difficult-to-work materials causes the nontraditional optics required for next-generation systems to be well beyond current fabrication capabilities—at an affordable cost. These defense-critical and defense-unique requirements must be met by systematically resolving the manufacturing technology issues and cost drivers that prevent the use of nontraditional optical shapes that will provide improved optical capability. Designers of combat systems will not be constrained by current design rules and a new class of war-fighting capabilities and weapon systems will evolve.

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1 Army Mantech—Optics Manufacturing Modernization Program.

2 DARPA Technology Reinvestment Program—Asphere Manufacturing Program.

3 Texas Instruments Missile Application Assessment Report—DARPA Physical Optics Program.

4 Boeing Aircraft Application Assessment Report—DARPA Physical Optics Program.

5 "Defense Manufacturing in 2010 and Beyond—Meeting the Changing Needs of National Defense, National Research Council," pp. 7–8.

6 *Defense Technology Area Plan,* 1997.

Australia	●	Canada	●	China	●●	Czech Republic	●●
France	●●	Germany	●●●	Israel	●●●	Japan	●●●
Russia	●●●	Singapore	●	South Korea	●	Sweden	●
Switzerland	●●	Taiwan	●●	UK	●●	United States	●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Japan, Israel, Germany, and Russia have significant R&D programs in this technology, followed by the United States, the Czech Republic, the UK, China, Taiwan, Switzerland, and France.

DATA SHEET III-11.3. LASER-AIDED SEMICONDUCTOR PROCESSING

Developing Critical Technology Parameter	To fabricate useful silicon carbide (SiC) semiconductor devices, several technologies must be developed. For example, to construct a junction field-effect transistor (FET), other FETs, or light-emitting diodes, the planner technologies of doping, oxidation, and metallization are needed, as well as patterning technologies. Laser-conversion technology has been found to be successful in generating conducting and insulating tracks (two basic elements of electric circuits) on SiC samples. Laser-doping technology can induce n- and p-type semiconducting properties in SiC. The parameters of interest are the crystal (cubic, hexagonal, and rhomohedral) structures of SiC and the laser fabrication/microprocessing parameters, for example, laser power, pulse length, scanning speed, solidification rate, nonequilibrium structures of SiC, and dopant implantation. The electrical parameters include voltage versus current characteristics, high-temperature annealing, and thermal stability of the SiC device.
Critical Materials	SiC, SiOC (silicon oxycarbide), $Si_{1-y}C_y$ structures, dopants (e.g., B, Al, N), AlN film, oxygen and inert gases for laser processing. SiOC and $Si_{1-y}C_y$ structures are produced during laser treatment to impart electrically conducting and insulating properties to the SiC surface. The AlN film deposited on SiC can be decomposed with a laser beam to implant aluminum and nitrogen into the SiC matrix in a single laser irradiation step. This will generate n- and p-type semiconductors and p-n junctions in a single laser microprocessing step.
Unique Test, Production, Inspection Equipment	The testing equipment includes a four-probe resistivity measurement instrument and an inert or vacuum furnace for testing the thermal stability of SiC devices and evaluating their electrical properties at high temperatures. Other testing equipment includes materials characterization tools such as the scanning electron microscope (SEM), atomic force microscope (AFM), and X-ray photoelectron scattering (XPS). The processing equipment include lasers such as continuous wave CO_2 and Nd:YAG lasers and pulsed lasers of nanosecond pulse length and shorter. The fabrication technique is unique (see the section on critical materials).
Unique Software	The software to scan the laser beam on the workpiece in a predetermined pattern is generally available. Laser process modeling software needs to be developed to understand the interaction of lasers with SiC and the formation of new structures with different electrical properties at the SiC surface. Such mathematical models will be useful in optimizing the processsing conditions and developing process control and monotoring systems.
Technical Issues	The technical issues that drive/significantly influence this technology are (1) new solid state devices for high-temperature operational capability, (2) new laser microprocessing technology to fabricate such devices, and (3) the reduction of size and cost of electronic equipment. The technical hurdles/challenges are (1) micropipe substrate defects; (2) dielectric deposition, etching, doping, and oxidation; and (3) metallization of source, drain, gate, interconnects, and vias. (continued)

Technical Issues (continued)

The technical approach to overcome these hurdles would be to develop laser-conversion technology to synthesize SiC insulators, semiconductors, and conductors in SiC substrates to produce devices and sensors (U.S. Patents Nos. 5345741 and 5837607).

The ability to use this technology is not constrained by a scarcity of professional, scientific, or technical personnel or skilled labor or other factors. However, this technology needs to be developed through systematic research, mathematical modeling, and device-characteristic evaluations.

The military application does not require specialized adaptation or further development of commercial technology.

Major Commercial Applications

The commercial applications of SiC device technology include high-temperature sensors for temperature, pressure, flow rate, and gas or liquid sensing. The following table summarizes some of the applications.

Table III-11.3. Current and Projected Operating Temperatures and Reliability of Electronic Devices

Applications	Current Operating Temp. (°C)	Future Operating Temp. (°C)	Targeted Reliability (h)
Automotive	125–140	165–250	10,000
Aircraft		125	200–10,000
Spacecraft	300	500	1,000–30,000
Oil logging	175	175	10,000–30,000
Geothermal Development	200	250–260	10,000–30,000
Power Electronics	125	250–500	10,000–30,000

Affordability

This should not be an issue based on current chip microprocessing technology.

RATIONALE

There has been a tremendous interest in SiC because of its potential application in electronic and optical devices. Compared to Si, SiC has superior properties for high-power, high-frequency, and high-temperature electronics applications. Conventional Si devices exhibit high losses because of low breakdown voltage and are limited for use below 150 °C. SiC exhibits a breakdown strength of about 4.5 kV (10 times higher than that of silicon), resulting in lower losses. SiC also operates at higher temperatures (approaching 650 °C) and is, therefore, considered the material of the future for high-temperature applications. Power semiconductor device applications include diodes, thyristors, transistors, and rectifiers. Since SiC has high thermal conductivity and SiC devices can be operated at high temperatures, the requirement for thermal management (e.g., cooling system) is reduced. This results in the reduction of size and weight, and the cost of thermal management hardware.

SiC technology contributes to military superiority because it enables use of low-weight, high-temperature electronics without being limited by the thermal management hardware equipment.

E. R. Brown of the DARPA Electronics Technology Office has highlighted the required development of wide bandgap semiconductors, particularly SiC, to enable solid-state electronics operating beyond 1 MW. Applications exist in this range of power for both military and commercial applications. Recent small business innovative research (SBIR) and small business technology transfer program (STTR) solicitation tasks address development issues with wide bandgap semiconductors.

Military applications of SiC high-power devices and circuits include uncooled switching devices and integrated circuits for electrical power transmission and distribution systems and more-electric aircraft. SiC-based inverter can provide power for the traction motors for hybrid- and all-electric vehicles.

Microwave devices made from SiC will exhibit high-power, high-frequency operation with higher package density and reduced cooling subsystem requirements. In addition to military application in tactical radars, commercial applications of semi-insulating SiC includes high-definition television (HDTV) transmitters for the broadcast industry and tube technology replacement in airport surveillance and tracking radars.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●	Canada	●	France	●●	Germany	●
Japan	●●	Russia	●●	South Korea	●	UK	●●
United States	●●●						

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The United States has the lead in this technology with a significant R&D program, followed by Japan, Russia, France, and the UK. Several other countries are sponsoring limited R&D efforts.

DATA SHEET III-11.3. OPTICAL FLUORIDE MATERIALS

<table>
<tr><td>Developing Critical Technology Parameter</td><td>
Fluorides are very important materials for optical applications. They are used in a wide range of applications such as lasers, optical fibers, nonlinear crystals, UV windows (as CaF_2), coating materials (as ThF_4), and recently as scintillators for detection of smuggled plutonium.
With their extended transparency into the deep UV, fluoride crystals are important for lithography. A new nonlinear fluoride crystal ($BaMgF_4$), when periodically poled, has demonstrated feasibility of conversion into the deep UV. Because of their lower energy phonons and longer lifetimes (high storage capacity), fluorides are important as efficient diode laser pumped lasers.
One major drawback in pursuing fluoride technology was that there have been no reliable sources of high-purity fluoride starting materials. This has changed in recent years, and the major technology impetus is on high-purity, low-absorption material. At the projected power levels, high-purity bulk material is still a requirement.
<table>
<tr><th colspan="3">BaY_2F_a3 μm Er and 4 μm Ho Lasers</th></tr>
<tr><th>Parameter</th><th>1999</th><th>Projected by 2010</th></tr>
<tr><td>Er: CW power (W)</td><td>1</td><td>10</td></tr>
<tr><td>Er: Pulsed Energy (J)</td><td>0.01</td><td>0.1</td></tr>
<tr><td>Ho: CW power (W)</td><td>0</td><td>1.0</td></tr>
<tr><td>Ho: Pulsed Energy (W)</td><td>0.005</td><td>>4.0</td></tr>
</table>
<table>
<tr><th colspan="3">Periodically Poled Nonlinear $BaMgF_4$</th></tr>
<tr><th>Parameter</th><th>1999</th><th>Projected by 2010</th></tr>
<tr><td>Wavelength Range (nm)</td><td>500–250</td><td>500–150</td></tr>
</table>
</td></tr>
<tr><td>Critical Materials</td><td>The critical materials are the high-purity fluorides needed for the growth of fluoride laser crystals. Critical materials for production of high-purity fluoride starting materials are high-purity oxides and carbonates, water-free hydrogen fluoride gas, platinum, platinum/rhodium, and monel for the hydrofluorinator parts.</td></tr>
<tr><td>Unique Test, Production, Inspection Equipment</td><td>N/A.</td></tr>
<tr><td>Unique Software</td><td>N/A.</td></tr>
<tr><td>Technical Issues</td><td>Even though 100-percent hydrogen fluoride is used, the process is safer because it involves only gas that is completely neutralized during the process and does not pose risks for the operators or to the environment. The resulting fluorides are crystalline materials, resistant to oxidation, with no dust formation. All fluoride laser crystals need be oxygen free to avoid scatter losses, and the only way to guarantee this purity is to start with pure fluoride materials.</td></tr>
</table>

Major Commercial Applications	The fluoride materials are used as starting materials for growth of laser crystals, non-linear crystals, optical windows, and scintillator crystals; for glass optical fibers; and for optical coatings. Critical materials for production of high-purity fluoride starting materials are high-purity oxides and carbonates, water-free hydrogen fluoride gas, platinum, platinum/rhodium, and monel for the hydrofluorinator parts. Oxides and carbonates of high purity are widely available.
Affordability	When the starting fluoride materials are of high quality, the crystal growth yield increases, cutting manufacturing costs.

RATIONALE

Contrary to oxides, fluorides are fragile, and their low thermal conductivity precludes their use in high-power applications. With the advent of laser diodes, however, fluoride laser crystals became important because of their superior storage capacity. They can, for example, be incorporated in a very compact laser system, which is important for nonproliferation surveillance. They are, for example, potential candidates for countermeasure applications, being the only systems that have a good chance of efficiently emitting in the 3- to 4-µm range, while being able to be incorporated in a compact and lightweight system. They are also filling a need for materials transparent in the deep UV.

One fluoride crystal, Ho:BaY2F8, which lases around 4 µm, will be assessed for countermeasures applications. This crystal will be pumped by another fluoride crystal. Both crystals are very dependent on the starting material's purity.

WORLDWIDE TECHNOLOGY ASSESSMENT

Brazil	●●	China	●●	France	●●	Germany	●●●
Italy	●	Japan	●●●	Russia	●●●	UK	●
United States	●●●						

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Fluoride laser crystals have been grown in Russia, Brazil, and France for at least a decade. The significant current R&D prgrams are being sponsored in the United States, Japan, Russia, and Germany. Recently, Japan, UK (Scotland), Italy, and Germany have started small crystal growth programs, mainly in YLF and LiSAF (chromium and cerium-doped). Currently, AC Materials, a small business affiliated with CREOL, has started commercially supplying these materials and fluoride crystals as well. CREOL and AC Materials cooperate in several projects developing new fluoride crystals through SBIR programs and other R&D subcontracts for U.S. companies. For example, CREOL is developing two mid-IR lasers based on BaY_2F_8, a low-phonon laser host.

DATA SHEET III-11.3. IR OPTICAL ELEMENTS

Developing Critical Technology Parameter	Bulk materials in combination with appropriate coatings materials, including transparent overlays for any portion of the 1- to 12-µm spectral band, with a strength greater than 48 Mpa (7 ksi), including the following properties for plate size >5-cm diameter and missile domes of any size: – Ability to withstand 2-mm diameter raindrop impacts at 2.5 cm/hr rate at Mach >1.0. – Ability to withstand heating rate >100 W/cm^2.
Critical Materials	Free-standing diamond. Gallium phosphide (GaP). Strengthened sapphire. Single-crystal silicon carbide. Aluminum oxy nitro (ALON).
Unique Test, Production, Inspection Equipment	Equipment for rapid polishing of IR windows and domes, especially diamond. Single-point diamond turning machines. Diamond deposition production equipment. Equipment for rain and sand testing and damage assessment.
Unique Software	None identified.
Technical Issues	Unique materials processing and polishing. Fabrication processes for making specially designed optical elements. Low-cost optical finishing. Fracture toughness and strength at temperature. Deterministic micro-grinding processes need developing.
Major Commercial Applications	Optical-quality bulk diamond is a possible microwave window for very high power transmitters.
Affordability	Optical quality diamond will remain very expensive for the foreseeable future, but its use will provide payback in terms of maintainability.

RATIONALE

Affordable IR windows for maneuvering systems are required to protect IR sensors from the environment. In particular, high strength for thermal shock resistance and rain and sand erosion at high speeds is required for protection of the sensors. Multispectral optical performance is required for longer range target detection and defeat of countermeasures. Particular military applications are for IR seekers, IR missiles, IR surveillance, FLIR window/dome, and IRST window/dome.

WORLDWIDE TECHNOLOGY ASSESSMENT

China	●●●	Finland	●●	France	●●	Germany	●●
India	●	Italy	●●	Japan	●●●●	Norway	●●
Pakistan	●	South Africa	●	South Korea	●●●	Spain	●
Sweden	●●	Taiwan	●●	UK	●●●	United States	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The United States and Japan have the lead in this technology with extensive R&D, followed by China, South Korea, and the UK with significant R&D. Other known programs are either moderate or limited.

DATA SHEET III-11.3. IR COATING MATERIALS

Developing Critical Technology Parameter	IR coating materials for protection in hazardous environments such as in rain-, sand-, and dust-erosion conditions. Improved fracture strength and stability. Antireflection capable and oxidation resistant at over 700 °C. EMI shielding or low-observable characteristics.
Critical Materials	Diamond. Sapphire. Stoichiometric carbon nitrite (C_3N_4). Zinc sulfide and zinc selenide.
Unique Test, Production, Inspection Equipment	Diamond deposition production equipment. CVD equipment. Physical vapor deposition-laser evaporation equipment. MBE equipment. Equipment for measuring absolute reflectance of ±0.1 percent. Equipment for rain and sand testing and damage assessment.
Unique Software	None identified.
Technical Issues	Unique processing of coating materials. Optimum material composition and diffusion to attain desired characteristics. Optimum design of multilayer stacks to attain desired transmission/reflection/ absorption characteristics.
Major Commercial Applications	None identified.
Affordability	Although more expensive than current coatings, the payback in durability and maintainability will offset the initial expense over the lifetime of the optical system.

RATIONALE

Affordable IR windows and domes for maneuvering systems are required to protect IR sensors from the environment. Special coatings allow sensor windows to operate in rain and sand environments without significant optical loss. Oxidation resistance at temperatures greater than 700 °C permit operation at speeds greater than Mach 4. Multi-spectral optical performance is required for longer range target detection and defeat of countermeasures. Particular military applications are for IR seekers, IR missiles, IR surveillance, forward-looking infrared (FLIR) window/dome, and IRST window/dome.

WORLDWIDE TECHNOLOGY ASSESSMENT

China	●●	France	●●●	Germany	●●	India	●
Italy	●●	Japan	●●●	Norway	●	Pakistan	●
South Korea	●●●	Sweden	●	Taiwan	●●	UK	●●●
United States	●●●●						

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The United States has the lead in this technology with extensive R&D efforts, followed by South Korea, France, Japan, and the UK. Other known efforts are moderate or limited.

DATA SHEET III-11.3. SPECIALTY TRANSPARENT MATERIALS

Developing Critical Technology Parameter	Specialty transparent materials for coating and/or filters. NLO elements. Selectable/variable bandpass or narrowband rejection in the 0.2- to 20-µm spectral region.
Critical Materials	Selected oxides and dielectrics (application dependent).
Unique Test, Production, Inspection Equipment	Controls for deposition of coatings and in-situ characterization of coatings. CVD. Sputter deposition. MBE deposition. PVD. Electron beam, ion beam, and laser-enhanced deposition. Ion plating and laser evaporation.
Unique Software	Software for control of coating deposition, especially thickness and composition.
Technical Issues	Unique deposition of materials and processing controls.
Major Commercial Applications	Medical and astronomical applications and eye safety.
Affordability	The primary extra expense will be for capital costs for precise processing control equipment. Once in place, the coatings can be produced in standard commercial coaters.

RATIONALE

Optimum operation of visible and IR sensors, especially under hostile conditions, is highly dependent on the availability of specialty transparent materials for coating and/or filters and NLO elements.

WORLDWIDE TECHNOLOGY ASSESSMENT

China	●●●	Finland	●	France	●●	Germany	●●
Italy	●	Japan	●●●	Norway	●	South Korea	●●
Sweden	●	Taiwan	●●	UK	●●	United States	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The United States has the lead in this technology with an extensive R&D effort, followed by China and Japan with significant R&D.

DATA SHEET III-11.3. NLO MATERIALS

Developing Critical Technology Parameter	NLO materials for wavelength/frequency conversion with spectral bandpass in the 1- to 12-µm region. Transmission of NLO material in this bandpass region is needed, and the development of NLO technologies in this region is severely inadequate to provide the materials currently needed for specific military applications.
Critical Materials	Critical materials for production of high-purity fluoride starting materials are high-purity oxides and carbonates, water-free hydrogen fluoride gas, platinum, platinum/rhodium, and monel for the hydrofluorinator parts. Oxides and carbonates of high purity are widely available. Isomorphs of potassium titynal phosphate phosphate (KTP), for example, High Purity: $KTiAsO_4$, $RbTiOAsO_4$, ZnGeP2 Quasi-phasemathed materials (QPM), e.g.: GaAs, ZnSe Periodically poled ferroelectrics, e.g.: $LiNbO_3$ (PPLN) AgGaSe2, AgGaS2, CdGeAs2, NLO polymers: ZnGeP2 Periodically poled KTP and $BaMgF_4$ BBP $BaMgF_4$ (Other NLO material in the 1- to 12-µm bandpass region)
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Technical Issues	Material homogeneity, stochiometry, and purity. Absorption—the convertible power density must be increased and the damage threshold improved. Spectral transmission. Unique materials and processing. Higher second- and third-order nonlinearity (third order for switching).
Major Commercial Applications	Industrial and medical lasers as well as microchip optical processes.
Affordability	Nonissue for these materials.

RATIONALE

NLO materials are needed to provide new and variable laser wavelengths in the 1- to 12-µm region of the spectra. These NLO materials need to be developed to fully utilize the potential of current lasers for specific medical, industrial, and military applications.

WORLDWIDE TECHNOLOGY ASSESSMENT

China	●●●●	France	●●	Germany	●●	Italy	●
Japan	●●●	Norway	●●	South Korea	●●	Sweden	●
UK	●●	United States	●●●●				

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

China and the United States have the lead in this technology with extensive R&D efforts, followed by Japan with significant R&D.

DATA SHEET III-11.3. HIGH-ENERGY LASER (HEL) OPTICAL MATERIALS

Developing Critical Technology Parameter	Materials for HEL components: mirrors, beamsplitters, and windows. Improved efficiency and run-time capability. Substrate diameter >0.2 m. Low water fused silica (<100 ppm water) for diameter <35 cm. Optical coatings with total loss from absorption and scatter (200 ppm).
Critical Materials	Si, SiC. Low water fused silica. Coating materials: ThF_4, ZnSe, SiO_2, TiO_2, ZrO_2, Nb_2O_5, Al_2O_3. ZuS, ZnSe, Al_2O_3.
Unique Test, Production, Inspection Equipment	Single-point diamond turning coating/vacuum chambers. Computer-controlled grinding and polishing. Characteristic equipment to measure absorptance (laser calorimetry), total integrated scattering (TIS), bidirectional reflectance distribution function (BRDF)—scatter reflectance.
Unique Software	None identified.
Technical Issues	For mirrors: very low absorption, low scatter, high reflection coatings, low stress (especially for large diameters up to 4 m, durable and stable). For substrates: homogeneous properties, low absorption, and low inclusion content-high purity. For beam splitters and windows: antireflection/bandpass coatings—durable, stable. Bonding techniques for larger substrates—mirrors only. Cooling technology.
Major Commercial Applications	Cutting and welding technology.
Affordability	Need long run time, so cooling is important and may affect cost.

RATIONALE

HEL optical materials are needed to provide new and variable laser wavelength transmission elements that can withstand the high level radiation impinging on them. These HEL optical materials need to be developed in order to fully utilize the potential of current lasers for specific medical, industrial, and military applications.

WORLDWIDE TECHNOLOGY ASSESSMENT

China	●●	France	●●●	Germany	●●	Italy	●
Japan	●●	Norway	●●	Russia	●●	South Korea	●●
Sweden	●	UK	●●	United States	●●●●		

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The United States leads in this technology with extensive R&D, followed by France with significant R&D.

DATA SHEET III-11.3. FERROELECTRIC LIQUID CRYSTAL (FLC) MATERIAL

Developing Critical Technology Parameter	Compact (size of a quarter), lightweight (grams), low-power FLC devices operating in the extended scattering mode (ESM) for optical modulation in the near- to mid-IR spectral range. Originally investigated as a "solid-state" replacement for a motor-driven, germanium disk chopper device for uncooled, focal plane array (FPA) detectors (8–12 µm wavelength regime). Operates by forward scattering, not polarization rotation—no polarizers required; ideal for IR applications where incident radiant energy is low. Square-wave optical modulation patterns can be produced at response rates ranging from 100 µs to several seconds. A 40-percent modulation depth of incident broadband 8–12 µm light has been demonstrated; performance improves with shorter incident wavelengths (3–5 µm to visible region).
Critical Materials	Need to develop FLC materials with both improved transmission characteristics in the mid-IR region (3–5 µm and 8–12 µm) *and* low operating voltage requirements. Special high-transmission conductive coatings are required for use with nonconductive, IR transparent substrates (e.g., ZnSe, BaF).
Unique Test, Production, Inspection Equipment	Diamant bridge for characterization of FLC spontaneous polarization and hysteresis. Optical test bench for temporal response characterization using broadband 8–12 µm IR source. Optical test bench for determining angular distribution of both modulated and off-state forward scattered light.
Unique Software	None—drive waveform generation software is commercially available.
Technical Issues	New FLC materials must be designed and synthesized to maximize mid-IR transmission in regions of interest (3–5 µm and 8–12 µm). Bulk material properties (viscosity, spontaneous polarization, helical pitch, mesophase range) must also be taken into account during material design stage to ensure low operating voltage requirements, fast response, and broad operating range. Angular dependence of forward scattering has been initially characterized in the visible (HeNe), but extensive mid-IR characterization must be undertaken to better understand device physics and make a realistic assessment of potential performance. Effects of temperature on device performance have not been characterized. Work needs to be done to understand effect of electrical drive waveform shapes and voltages on FLC scattering characteristics in order to optimize performance at desired wavelengths of operation. As modulation components for uncooled FPA detector-based imaging devices (night vision goggles, rifle sights, and surveillance equipment). As an electro-optical defocusing device for power limiting and sensor protection. Any high-speed electro-optical modulation applications that can use forward scattering as the optical modulation mechanism in the visible or near-IR regions.

Major Commercial Applications	None identified.
Affordability	Drive electronics hardware and software are commercially available. Conventional liquid crystal display (LCD) manufacturing techniques can be used to assemble these devices.

RATIONALE

For imaging applications employing uncooled FPA detectors, obtaining further reductions in size, weight, and power requirements without sacrificing performance is paramount. The current technology employs a motor-driven, rotating mechanical chopper containing a germanium disk with a series of lenslet arrays ground into its surface at various positions to alternately defocus (diffuse) and transmit the incident IR radiation. Replacement of this mechanical chopper with a compact, low-power, solid-state modulator scalable to detector size would be highly desirable. Liquid crystal (LC) devices capable of modulation by forward scattering are an excellent alternative for this application due to their low power consumption, short path-length requirements, scalability of size, and excellent transmission characteristics in many regions of the near- and mid-IR. For both dynamic scattering in nematic LCs and the cholesteric-nematic phase transition, temporal response times are too slow for this application. Only FLCs operating in the extended scattering mode (ESM) have demonstrated the capability of modulating incident IR radiation optical radiation by forward scattering at sufficiently rapid temporal rates. The duration and frequency of the scattering state in FLC ESM devices can also be readily controlled by drive waveform shaping to produce a square-wave optical response with pulse periods of hundreds of microseconds. Although FLCs generally exhibit lower transmission in the 8–12 µm region of the IR than do their nematic counterparts, FLC transmission characteristics can be substantially improved by designing molecular structures in which 8–12 µm chromophoric linkage groups (e.g., C–O, C–N, O–H, and N–H bonds) have been minimized or completely eliminated. Using this design philosophy, ferroelectric liquid crystal compounds that show a 30-percent improvement in 8–12 µm transparency, as compared to commercially available materials, have been synthesized. Similar improvements in the 3–5 µm area are also possible if materials with by perfluorinated terminal groups are used. Considerable work still remains to be done both in improving IR transparency of FLCs and in understanding the effect of electrical drive waveform shapes and voltages on FLC scattering characteristics to optimize performance at desired wavelengths of operation. These FLC ESM devices can be valuable for any high-speed electro-optical modulation applications that can make use of forward scattering as the optical modulation mechanism in the visible or near-IR regions.

WORLDWIDE TECHNOLOGY ASSESSMENT

China	●●●	France	●	Germany	●	Japan	●●
Russia	●	Singapore	●	South Korea	●	Taiwan	●
UK	●	United States	●●				

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

China leads in this technology with significant R&D, followed by the United States and Japan with moderate R&D efforts.

DATA SHEET III-11.3. POLYMER LIQUID CRYSTAL FLAKE MATERIAL

Developing Critical Technology Parameter	Polymeric cholesteric liquid crystal (pCLC) films, when fractured into “flake” form, can be used as “polarizing pigments” to produce coatings with unique optical properties. The flake form maintains all of the advantageous physical properties of the parent pCLC film (temperature insensitivity, physical and chemical robustness, and selective reflection). pCLC materials with selective reflection wavelengths ranging from the visible to the near IR are readily available either in single-component form or by blending. pCLC flakes can be produced in sizes from a few to hundreds of micrometers in cross-section as needed for any particular application. When pCLC flakes are prepared by photolithographic curing of reactive LC monomers, “patterned particles” can be formed in different sizes and shapes with numbers, letters, or other patterns encoded on the flake surface. When suspended in a fluid host, pCLC flakes can be reoriented by either AC or DC electric fields to produce a change in selective reflection color. Only a few degrees of flake rotation are required to see a substantial change in reflection properties. Encapsulation of the pCLC flake/fluid suspension into a binder would produce an electrically-addressable conformal coating material that could be switched between two (or more) reflective (or colored) states, depending on the properties of the flake/fluid host system.
Critical Materials	pCLC flake materials derived by thermal and mechanical fracturing of pCLC films. pCLC “patterned particles” prepared by photolithographic curing of reactive LC monomers. A fluid host. An encapsulation binder. Agents to help prevent particle agglomeration and enhance switching uniformity.
Unique Test, Production, Inspection Equipment	Film-casting equipment for preparing pCLC films (knife coater, roll-coater, or slot-die coater). Thermomechanical film-fracturing equipment for forming flakes from prepolymerized pCLC films. Particle sizing and sorting equipment (e.g., sieve shakers). Particle size distribution characterization equipment. Photolithographic equipment and UV sources for producing patterned pCLC flakes. Dispersing equipment for encapsulation of pCLC flake/fluid suspensions in polymer binders. Test benches for characterization of device response time, drive voltage requirements, and optical contrast.
Unique Software	None identified.

Technical Issues	Several passive pCLC flake device applications have already been demonstrated (e.g., vehicle paints). pCLC flake electro-optical switching has only been demonstrated over a small active area; considerable work remains in demonstrating highly uniform switching over a large active area. Long-term stability of flake/fluid systems has not been determined. Electro-optical switching of patterned flakes in a host system has yet to be demonstrated. Encapsulation of pCLC flake/fluid suspensions in a polymer binder has not yet been attempted. Passive reflective pigments with unique optical polarization properties for the visible region (decorative, anticounterfeiting, document security, and identification). Electrically switchable conformal coatings for camouflage, signature reduction, information displays, reflection control, privacy windows, identification, coding, and information storage.
Major Commercial Applications	Passive reflective pigments with unique optical polarization properties for the visible region (decorative, anticounterfeiting, document security, and identification). Electrically switchable conformal coatings for camouflage, signature reduction information displays, reflection control, privacy windows, identification, coding, and information storage.
Affordability	All materials (pCLC flakes, fluid hosts, and encapsulation binders) are commercially available in large quantities at low cost.

RATIONALE

Coatings technology plays an important role in many military operations as well as in the private sector. Coating materials with special optical properties that could be electrically switched are of special interest in emerging military and commercial applications. A unique form of liquid crystal technology is based on the formation of particles, or flakes, generated by thermal fracturing of pCLC films. These flakes exhibit optical properties identical to the parent films from which they were derived, and because they originate from an aligned CLC polymer film that has a relatively high glass transition temperature (T_g), their selective reflection wavelength, birefringence, and alignment quality are “frozen-in” and are thus essentially insensitive to thermal or mechanical disruptions. Because the selective reflection colors are highly saturated and show a dependence on the angles of illumination and observation, their visual appearance has been used as the basis for art or the manufacture of commercial products like paints and cosmetics. For cross-linkable pCLC materials, specialized curing cycles can be used to induce a *pitch gradient* into the CLC film. By controlling the gradient of the pitch, films have been developed that show broad reflectance bands ranging from the visible to the near IR. This attribute opens up the possibility for their use as broadband, nonabsorptive polarizers in LC displays. The unique optical properties of these flakes can be transferred to other polymer systems by dispersing the flakes into a solution of the polymer host and using it as a “binder.” This process has been used to prepare passive (i.e., nonswitchable) conformal coatings with unusual optical properties for applications ranging from document security to exterior coatings for motor vehicles. If a suitable quantity of pCLC flakes with appropriate physical, chemical, and optical properties are dispersed into a fluid host medium in which the pCLC flake is insoluble, the pCLC flakes can be *reoriented* in the presence of an applied electric field, with a resultant change in the optical properties (i.e., selective reflection color) of the device. The mechanism for orientation depends on the composition of the pCLC flake material and the host material in which it is dispersed. Such an electrically tunable optical polymer system could find applications in a number of key technology areas, including switchable coatings for applications in military security, camouflage, substrate reflectance control, document security and anticounterfeiting, and object tagging and identification. Other applications in information displays for either flat or curved surfaces (large-area signs, automobile dashboards, heads-up displays) or as switchable and tunable devices for color manipulation or polarization control are also possible.

WORLDWIDE TECHNOLOGY ASSESSMENT

Canada	●	China	●●●	France	●	Germany	●
Japan	●●●	Singapore	●	South Korea	●	Taiwan	●
UK	●	United States	●●●				

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

China, Japan, and the United States lead in this technology with significant R&D efforts.

DATA SHEET III-11.3. HIGH-ACCURACY, THIN-FILM IR OPTICAL COATINGS

Developing Critical Technology Parameter	Improved yield of complex multilayer coatings using stabilized processes and real-time error correction. Provide multilayer optical coatings with multiple spectral requirements for high- or low-power laser applications. Make process available to optics system integrators. Process capable of rapid development time for complex coating designs.
Critical Materials	Materials for coatings that exhibit stable accurate characteristics during deposition and good IR properties.
Unique Test, Production, Inspection Equipment	Mid-IR detector-array spectrometers for real-time in-situ monitoring, 1.7–12 µm. Software drivers for interface to detector array.
Unique Software	None identified.
Technical Issues	Optimization and characterization dynamic link library (DLL) modules that are computationally intensive but very fast. Current routines are written and owned by a group from Moscow State University Success of this technique would be dependent on finding a deterministic, stable coating process. Three methods should be explored: – E-beam deposition, – Ion-assisted E-beam deposition, and – Magnetron sputtering. Once process/material is identified, the process is optimized using both in situ optical monitoring and multiple crystal arrays to monitor vapor plume. All systematic errors in process are first identified using reverse engineering methods. Random and measurement errors are then determined and quantified. Real-time error correction may then be used on the stabilized process.
Major Commercial Applications	This has a high potential for commercial applications and could be retrofit to existing coating equipment.
Affordability	Because this technology is expected to reduce production cost and improve yield, it will pay for itself in a short time.

RATIONALE

Optical coatings are used in practically all optical systems. Military optical systems make extensive use of the mid-IR region of the spectrum. A high-precision deterministic coating process has been developed specifically for the use of high-power fusion lasers in the UV, visible, and near-IR range. This system also has a capability of automatically correcting errors that have been made during the coating process. The error-correcting system is particularly useful for complex designs with many layers that may be coated onto costly substrates. A system can be developed which designs and fabricates a coating, observing the characteristics of the coating and correcting any errors made during the fabrication. The system would be based upon a highly developed process that could be used for a wide variety of coating requirements in military optics.

Despite the obvious need in the industry, fewer and fewer individuals are opting to study coating design, and there are no institutions in the United States granting Ph.D.s in the field of optical coating design. Given this shortage of expertise, it would be useful to have equipment that is capable of both the design and fabrication tasks for a systems integrator.

WORLDWIDE TECHNOLOGY ASSESSMENT

China	●●	France	●●	Germany	●●	South Korea	●●
Taiwan	●●	UK	●●	United States	●●●		

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The United States leads in this technology with significant R&D, followed by China, Taiwan, France, Germany, the UK, and South Korea with moderate R&D efforts.

DATA SHEET III-11.3. TRANSITION METAL DITHIOLENE DYE MATERIAL

Developing Critical Technology Parameter	Nickel dithiolene near-IR dyes are zerovalent transition metal complexes that are highly soluble in LC hosts. When synthesized with appropriate terminal groups, transition metal dithiolenes can possess liquid-crystalline properties on their own; this allows them to be added to LC host materials in high concentrations without affecting the ordering of the host material. Dichroic switching with a contrast ratio of 5:1 and a blocking extinction of optical density (OD) 3.5 at 860 nm has been demonstrated in a commercially available LC host containing a mesogenic nickel dithiolene 780 nm. The near IR_{max} transition metal dithiolenes is extremely strong ($\varepsilon < 50,000$) and can be adjusted by synthesis to between 600 and 1,500 nm. Nickel dithiolenes with chiral terminal groups can function as a *chiral dye* and can induce a cholesteric phase when added to a nematic LC host.
Critical Materials	Nematic liquid-crystal host suitable for electro-optical applications (e.g., broad temperature-range mixture with positive or negative dielectric anisotropy). Transition metal dithiolene dyes with appropriate terminal groups to (1) enhance solubility in an LC host, (2) induce liquid crystalline properties in the dye itself, or (3) induce chirality in the LC host.
Unique Test, Production, Inspection Equipment	Equipment for fabrication of LC devices (spin-coater, alignment layer buffing machine, Class 100 clean room area, and ovens). Electro-optical characterization test bench (contrast ratio, response time).
Unique Software	None identified.
Technical Issues	High-contrast dichroic switching at both 780 and 860 nm has been demonstrated in a commercially available LC host containing a mesogenic nickel dithiolene; optical modulation has recently been demonstrated at 1,054 nm using a nonmesogenic nickel dithiolene dye in an LC host. Induction of cholesteric mesophase by addition of nickel dithiolene with chiral end-groups to a nematic host has only recently been demonstrated in one system. Switching behavior has not been characterized. *Nickel* dithiolene complexes enhance conductivity of the LC host when added in high concentrations, which is detrimental to LC device operation. Palladium and platinum derivatives are much less conductive and would be better choices; however; these are considerably more difficult to prepare, and only a few examples exist in the literature. The materials are not commercially available and must be designed with appropriate physical properties and synthesized.
Major Commercial Applications	Optical modulators for near IR communications. Shutters, choppers, and modulators for near-IR wavelengths. Guest-host switchable polarizers for the near IR. Active element in a point-diffraction interferometer. Switchable circular polarizer or notch filter (chiral dye). Tunable blocking filters for sensor protection.

Affordability	Primary cost is in synthesis and development of the dyes. Devices utilize standard LC materials, equipment, and techniques used in fabrication of commercial LCDs.

RATIONALE

There is considerable interest in LC devices capable of modulating or otherwise affecting the properties of incident radiation in the near-to-mid IR region. Although applications exist for guest-host LC devices with such a capability in both the commercial and military sectors in areas such as free-space IR communications and sensor protection, there has been little recent activity in this area with respect to LC devices. A primary reason for this relative inactivity is that there is a severe lack of near-IR dyes with (1) sufficient solubility in the LC host, (2) low impact on the inherent order of the LC phase, (3) good thermal and chemical stability, and (4) a large absorbance maximum that can be tuned by structural modification over a broad range of the near-IR region. Transition metal complexes based on a nickel, palladium, or platinum dithiolene core show substantial promise in meeting the above-mentioned requirements. Because these materials are zerovalent, they exhibit high solubility in LC hosts (up to 10 percent weight percentage) and, with certain terminal functional groups, can exhibit their own liquid crystal phases. The λ_{max} in these materials can range from 600 nm to 1,500 nm, depending on structure. The recent synthesis of a nickel dithiolene dye with chiral end groups has shown that these dyes can induce a chiral mesophase in a nonchiral nematic host. This finding opens the possibility of generating novel LC mixtures with two *degrees of tunability*—an electronic absorbance band tunable by synthesis and a selective reflection band tunable by temperature or applied electric field. Such a materials system would be particularly advantageous in sensor protection for dealing with frequency-agile laser threats.

WORLDWIDE TECHNOLOGY ASSESSMENT

Canada	●	China	●●	France	●	Germany	●
Israel	●	Japan	●●●	Russia	●	Singapore	●
South Korea	●	Sweden	●	Taiwan	●●	UK	●●
United States	●●●						

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Japan and the United States lead in this technology with significant R&D, followed by the China, Taiwan, and the UK with moderate R&D efforts.

SECTION 11.4—SUPPORTING TECHNOLOGIES AND APPLICATIONS

Highlights

- Integrated design, fabrication, test, and assembly methods will permit the transition of today's hybrid optical devices into the fully integrated optical systems required for miniaturization and high performance.
- Optical tape recording will provide data and image recording capability of 160 MB/sec.
- Full color UXGA display format (600 × 1,200 pixels) head-mounted displays are expected by 2004.
- Technology to provide high-quality night vision systems without large pixel image sensors is underway.
- A means for rapidly detecting nuclear explosions and chemical/biological weapons is proposed, using the free electron laser.

OVERVIEW

This section provides a variety of applications, test facilities, and component developments that marry lasers and optics. They range from atmospheric probes, display technology, and optical recording to molecular cooling using lasers. These applications do not fit neatly into the other four sections of Lasers and Optics; more such technologies are expected to be added with the explosive growth of the area.

RATIONALE

Optics and lasers in combination provide many new opportunities and technical challenges that are both high pay-off and enabling technologies. Key technical challenges for optical components include integrated design, fabrication, assembly, and test methods, which permit the smooth transition of the hybrid micro-optical devices of today into the fully integrated optical systems required for miniaturization and to meet high performance goals of future military products.

Country	Sec. 11.4 Supporting Technologies and Applications
Australia	●
Canada	●
China	●
France	●●
Germany	●●
India	●
Israel	●
Italy	●
Japan	●●
Netherlands	●
Norway	●
Poland	●
Russia	●
Singapore	●
South Korea	●
Sweden	●
Switzerland	●
Taiwan	●
UK	●●
United States	●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Figure 11.4-1. Supporting Technologies and Applications Systems WTA Summary

LIST OF TECHNOLOGY DATASHEETS
III-11.4. SUPPORTING TECHNOLOGIES AND APPLICATIONS

The following developing technologies are very early in the research phases, so numerical values and specific goals for some of the critical parameters have not yet been identified or determined at this time.

DATA SHEET III-11.4. OPTICAL TAPE RECORDING TECHNOLOGY

Developing Critical Technology Parameter	Recording data rate >1,300 Mbit/sec. HDTV places the greatest current commercial demands on recording technology. The real-time output of an HDTV camera is approximately 1,300 Mbit/sec, well beyond the capability of standard digital magnetic tape-recording techniques. Archival HDTV recording currently employs data compression to reduce the data rate down to approximately 150 Mbit/sec. However, the compression algorithm is very lossy—the original 1,300-Mbit/sec data stream cannot be fully reconstructed.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Technical Issues	Development of a lossless compression algorithm. Demonstrate 160 MB/sec data rate.
Major Commercial Applications	HDTV.
Affordability	The optical tape recorder is expected to be less expensive than a magnetic recorder. The cost of the higher density tape cassettes is expected to be about the same as the current lower density magnetic tape cassettes.

RATIONALE

> *To meet the rigorous information demands of the warfighter, commander and National Command Authority (NCA) in 2020, a system and architecture must exist to provide a high resolution "picture" of objects in space, in the air, on the surface and below the surface—be they concealed, mobile or stationary, animate or inanimate. The true challenge is not only to collect information on objects with much greater fidelity than is possible today, but also to process the information orders of magnitude faster and disseminate it instantly in the desired format.*
>
> *Air University SPACECAST 2020 Technical Report.*

Full exploitation of high-resolution pictures requires the ability to acquire, store (record), and display with equal resolution. Recording technology lags the other two technologies.

In addition to the recording of imagery, a continuing requirement of the intelligence community is to store enormous amounts of data currently archived on magnetic tape, which has a far lower recording density than optical recording. The volumetric ratio of optical to magnetic tape is approximately 20/1.

The technology will be accessible to DoD. The commercial HDTV-related effort derives from a 50/50 cost-sharing grant from the National Institutes of Science and Technology (NIST). A DoD program to exploit optical archival recording is being sponsored by the intelligence community on behalf of all DoD potential users. A consortium of five companies led by LOTS Technologies, Sunnyvale, California, is executing the NIST program. They have demonstrated many of the individual techniques on an optical bench. Other firms involved are Avid, Pluto, Polaroid, and Lucent.

The industrial participants in the DoD program are LOTS Technologies, Kodak, and TRW. The interest here is in a straight data recorder without regard to format; it will be a general-purpose recorder.

In 1999, the DoD program has demonstrated a 25-MB/sec prototype, and Kodak has established a reliable, low-cost production capability for optical tape. The Phase 2 goal, to be started in 2000, will demonstrate a 160-MB/sec data rate using optical tape on reels holding 1.6 terabytes.

WORLDWIDE TECHNOLOGY ASSESSMENT

France	●	Germany	●	Japan	●	UK	●
United States	●●●●						

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

No related R&D has been identified outside the United States. Other nations identified have existing capability in magnetic tape recording; hence, they are the most likely to initiate programs in optical tape recording.

DATA SHEET III-11.4. HETEROGENEOUS INTEGRATION OF VERTICAL CAVITY SURFACE EMITTING LASERS (VCSELs) AND PHOTODETECTORS WITH COMPLEMENTARY METAL OXIDE SEMICONDUCTOR (CMOS) CIRCUITRY

Developing Critical Technology Parameter	Optical interconnections allow the development of terabit optical links for higher density computers. Pixel-based processors allow imaged analysis over 1 million times faster than conventional CCD cameras. Heterogeneous Integration of VCSELs and photodetectors with CMOS circuitry.
Critical Materials	CMOS circuitry. High-performance VCSELs and photodetector epilayer material.
Unique Test, Production, Inspection Equipment	High-speed digital test equipment. Electro-optic test equipment.
Unique Software	None identified.
Technical Issues	Advance architecture. Optics design. Electo-optic processing techniques.
Major Commercial Applications	Parallel processing. Image processing. Optical interconnects. High-density computing systems.
Affordability	Affordability will depend on the desired complexity of the system and must be tailored to meet the appropriate needs.

RATIONALE

Data acquisition of a 100 × 100 miles square region with 10 bits of terrain information per square foot requires 2.8 Tbits of information. Providing terabit optical links would allow for real-time retrieval, storage, and computation of this data, which is desired in battlefield situations. Increasing computational ability provides a technical advantage for a variety of critical objectives. Also, the small size and light weight of this dense computing system makes it ideal for micro air vehicles.

WORLDWIDE TECHNOLOGY ASSESSMENT

Canada	●	Japan	●●	UK	●	United States	●●

Legend:	Extensive R&D	●●●●	Significant R&D	●●●	Moderate R&D	●●	Limited R&D	●

The major activity is primarily limited to the United States and Japan and the main motivation is commercial. This is one of many options for optical interconnects.

DATA SHEET III-11.4. QUANTUM NANO-OPTICS OF SEMICONDUCTORS (QNOS)

Developing Critical Technology Parameter	Joining linear nano-optical techniques and semiconductor growth and fabrication capabilities to produce semiconductor microcavities in the quantum regime. Pushing the technology of semiconductor microcavities to small volumes (less than 1 cubic µm). Developing quantum dots (100–200 nm diameters) with large dipole moments and short radiative lifetimes.
Critical Materials	Large "perfect" quantum dots with large dipole moments ideal for light matter interaction. Improved semiconductor crystal quality will have longer coherence length important for quantum interference devices and larger coherence areas. There is a requirement for high-finesse 3–D nanocavities with guided mode cutoffs such that "Beta" is on the order of 1, where Beta is the fraction of total light going into the desired cavity mode.
Unique Test, Production, Inspection Equipment	Solid-immersion lenses used for photoluminescence excitation and NLO characterization of single quantum dots and quantum-dot nanocavities with nominal 0.25 µm spatial resolution. External mirror fabricated by MEMS for making a 10-µm long single-quantum-dot microcavity. Evaluation techniques include scanning tunneling microscopy (STM) luminescence excitation (similar to photoluminescence excitation, except the excitation is done through the tunneling tip and detected by the resultant luminescence). Near-field scanning optical microscopy is also needed for evaluations.
Unique Software	Software will need to be developed to solve the many-body theory of trade-offs for quantum dot dipoles vs. size of the quantum dot for 1-photon interactions.
Technical Issues	To build a solid-state implementation of a single atom in a microcavity able to exhibit entanglement and a quantum phase gate in which a single control photon changes the transmission for a single probe photon.
Major Commercial Applications	Active displays emitting light and not relying on reflected light will use this technology. Higher density memories and lower energy switching technology require this technology for efficient systems. Since QNOS essentially reduces the size and energy requirements of optoelectronic devices, it is certain to have spinoffs in implanted sensors, memories in general, and control devices such as small computer modules.
Affordability	As electronic and optoelectronic devices are made smaller and smaller, quantum effects will become increasingly important. It is a wise investment to have physicists, material scientists, and computer scientists developing cost-effective techniques and technology now.

RATIONALE

In the near term (1–5 years) this technology is expected to produce the lowest threshold VCSEL nanolasers, nanoLEDs with high efficiency and very low power consumption, and the lowest energy optical switches. In the longer term (5–20 years) this technology is expected to provide nonclassical light sources, entanglement systems, quantum phase gates, and amplifiers for quantum teleportation of entangled signals. The importance to military systems is the impact this will have on battlefield electro-optical systems and telecommunications. Smaller electronic and optoelectronic devices mean that the soldier, as well as missiles, for that matter, can have much greater computing and communicating capability while carrying lighter equipment.

WORLDWIDE TECHNOLOGY ASSESSMENT

Japan ●●● United States ●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Quantum optics is a field that will take 10 to 20 years to mature. Considerable research interest exists in many countries worldwide. The following site provides links to many of these. Because the field is still in early development, most countries are given equal R&D ratings.

Quantum Optics and Atom Optics links

http://www.theo1.physik.uni-stuttgart.de/~liebman/qolinks.html

BACKGROUND

The following is a list of facilities with experience in quantum optics. The list is sorted by country, university, center, etc., as applicable; and field of research or name of laboratory or group conducting the research.

- ***Australia***

  Australian National University
  Atom Manipulation Project;
  Atom Optics;
  Optics Research

  Macquarie University
  Quantum Optics

  MelbourneUniversity
  Atom Optics Group
  Photonics Research Laboratory

  Queensland University
  Laser Cooling and Trapping
  Theoretical Quantum Optics

- ***Austria***

  Innsbruck University
  Anton Zeilinger's Quantum Optics Group
  Peter Zoller's Theoretical Quantum Optics Group

- ***Belgium***

  P. Mandel's Quantum Optics Group

- ***Canada***

  Ontario Laser and Lightwave Research Centre

  Montreal University
  Lab for Theoretical and Quantum Computing

  Toronto University
  Laser Physics and Quantum Optics

- ***Denmark***

  Aarhus University
  Theoretical Quantum Optics Group

- ***Finland***

  Helsinki University
  Quantum Optics Group

- ***France***

  L'École Normale Superieure
  Le Laboratoire Kastler Brossel

  Institut d'Optique, Orsay
  Quantum Optics Group

- ***Germany***

  Abert Ludwigs-Universität, Freiburg
  Theoretische Quantendynamik

  Freiburg University
  Quantum Stochastics

  Ludwig Maximilans Universität, München
  Theoretical Quantum Optics

  Max Planck Institut für Quantenoptik, Garching
  Theoretical Quantum Optics Group

  Universität Konstanz
  Jurgen Mlynek's Group
  Quantum Metrology Group

- ***India***

  Physical Research Laboratory, Ahmedabad
  Laser Physics and Quantum Optics Group

  Institute of Mathematical Sciences, Madras
  Optics Group

- ***Israel***

  Weizmann Institute
  Quantum Optics Group

- ***Japan***

  Kyoto University
  Quantum Optics Group

- ***The Netherlands***

  Eindhoven University of Technology
  Atom and Quantum Optics
  Theoretical Atomic Physics and Quantum Electronics

- ***New Zealand***

  Otago University
  Laser Physics and Quantum Optics Group

- ***Russia***

  Lebedev Physical Institute, Moscow Quantum Optics Group

- ***Spain***

  Universidad de Salamanca
  Optics Group

- ***UK***

  Essex University
  R. Loudon's Nonlinear and Quantum Optics Group

  Imperial College, London
  Peter L. Knight's Laser Optics and Spectroscopy Group

  Oxford University
  Chris Foot's Laser Cooling Group
  Keith Burnett's Atomic and Laser Physics Group
  Quantum Computation and Cryptography

  Strathclyde University
  Nonlinear and Quantum Optics

- ***United States***
  - ***Alabama***

    U.S. Army Missile Command, Redstone Arsenal
    Chuck Bowden's Quantum Optics Group

  - ***California***

    California Institute of Technology
    Jeff Kimble's Quantum Optics Group
    Ken Libbrecht's Atomic Physics Group

    University of California, Berkeley
    Raymond Y. Chiao's Quantum Optics Group

    University of California, Los Angeles
    Quantum Information page, Center for Advanced Accelerators

    Stanford University
    A. E Siegman's Group
    ERATO Quantum Fluctuation Project

  - ***Colorado***

    University of Colorado at Boulder and JILA
    Center for Theoretical Atomic, Molecular, and Optical Physics

    JILA
    Atomic Physics

  - ***Connecticut***

    University of Connecticut
    Phil Gould's Laser Cooling Group
    Theoretical Optical Physics

    Yale University
    Atomic Physics and Quantum Optics

  - ***Florida***

    University of Miami
    Quantum Optics Laboratory

  - ***Louisiana***

    Louisiana State University
    Atomic Physics

  - ***Maryland***

    University of Maryland
    Quantum Optics Group

    NIST
    Electron Physics Group

  - ***Massachusetts***

    Boston University
    Philosophical Foundations of Physics Group

    Harvard University
    Mara Prentiss Group (Atom Optics)
    The Consortium for Light Force Dynamics (also at NIST)

- ***Michigan***

University of Michigan
Atomic, Molecular, and Optical Physics

- ***New Mexico***

Los Alamos National Laboratory
Quantum Information Group

- ***New York***

State University of New York, Stony Brook
Experimental Atomic, Molecular, and Optical Physics and Quantum Electronics

University of Rochester
Carlos Stroud's Quantum Optics Group
Institute of Optics
Leonard Mandel's Quantum Optics Experimental Group
Quantum Optics Group
Rochester Theory Center for Optical Science and Engineering
Shaul Mukamel's Optics Group

- ***Oregon***

Oregon State University
Atomic, Molecular, and Optical Physics

University of Oregon
Howard J. Carmichael's Quantum Optics Theory Group
Mossberg Laboratory
Raymer Laboratory

- ***Texas***

Rice University
Atom Cooling (Bose-Einstein Condensation)

University of Texas
Mark Raizen's Quantum Optics and Atom Optics Group

- ***Virginia***

University of Virginia
The University of Virginia Laboratory for Optics and Quantum Electronics

- ***Wisconsin***

University of Wisconsin
Atom Trainers

DATA SHEET III-11.4. HIGH-RESOLUTION MICRODISPLAY TECHNOLOGY USING FLCs ON CMOS SILICON

Developing Critical Technology Parameter	High information content microdisplays for near-to-eye and projection applications are of military and commercial interest. FLCs provide an outstanding electro-optic modulation layer, and when integrated with CMOS silicon backplanes, provide outstanding performance in binary light modulation. While binary modulators running at high frequencies can provide full color and gray scale by temporal averaging, combination of the high switching speeds, characteristic of FLCs, with true analog modulation would be very attractive for high-quality information displays. Achieving this goal requires development of new materials and device geometries. Technology is developing to eliminate color break-up or other undesirable artifacts of the time-sequential driving scheme. A full-color frame rate of 1.5 kHz (pixel refresh rates of 50 kHz) is required. Analog FLC-based devices for optical correlator applications such as fingerprint recognition or person recognition (e.g., in security systems for large installations) and photonics applications such as beam steering will be available as prototypes in 2001. High-resolution analog modulators for optical correlators and beam steering will be available in 2003.
Critical Materials	FLCs and special alignment materials.
Unique Test, Production, Inspection Equipment	Fourier transform infrared (FTIR) microscope, optical microscope, synchrotron X-ray source (the microscopy equipment will be customized for our purposes, but the basic equipment is not unique).
Unique Software	Optical simulation software, that is, software for large-scale simulation of liquid crystals, is unique. Critical parameters in this case are materials and devices. Design of FLC materials is aided by the LC simulation software, while design of optical devices is aided by optical simulation software. While progress can be made absent the software, time to develop the targets is lessened with good software tools. These tools are thus critical to meet the timelines implied above.
Technical Issues	Regarding bistable FLC/Si devices, the key technical issues now revolve around alignment and cell design. There is a scarcity of technical personnel to address the issues involved. Delivery of the necessary capabilities for first-generation devices has occurred. Improvements with regard to reliability, lifetime, and quality require delivery and assimilation of new technology. This should occur by 2001. Analog FLC/Si is much less mature. Basic technical blocks at the material and device levels are present. Technology for first-generation materials and devices (this is really second generation—though first-generation solutions are not usable in real-world applications) should be available in 2002. An approach for analog modulation must be adopted, then specialized materials and devices fabricated and tested. Eventually, custom analog CMOS backplanes must be fabricated just to demonstrate the approach. Actual production would then follow.
Major Commercial Applications	HDTV, head-mounted computer displays, rear-projection computer displays, high-resolution front-projection systems, optical correlators for machine vision, and beam steering devices.
Affordability	In volume, FLC on silicon chips could be as inexpensive as dynamic random access memory (DRAM). The cost of illumination and optics depends upon the application. There is clearly a substantial cost benefit relative to large-area direct-view analog modulation LCDs.

RATIONALE

Binary FLC on silicon microdisplay-based commercial products will become available next year. These will include very small digital cameras with FLC/Si viewfinders as key elements and HDTV sets using microdisplays in rear-projection. By the year 2002 very high resolution head-mounted displays based upon FLC/Si chips should be available. By the year 2004 full-color UXGA (1,600 × 1,200 pixel) head-mounted displays for voice-controlled portable computing will be available.

Bistable FLC/Si in combination with projection optics or near-to-eye optics and illuminators could replace the CRT as the standard for information display in all military and commercial applications. In addition, analog spatial light modulators with world-class performance for optical signal processing, image analysis, and beam steering could be produced.

WORLDWIDE TECHNOLOGY ASSESSMENT

China	●●	France	●●	Germany	●●●	Japan	●●●●
UK	●●●	United States	●●●●				

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The indicated countries have commercial firms that are also engaged in advanced development activities.

Commercial web sites

United States

http://www.microdisplay.com/

http://www.kopin.com/

http://www.comicro.com/

UK

http://www.meko.co.uk/

China

http://www.varitronix.com/

Japan

Japanese Display Report

http://www.meko.co.uk/interlingua.html

Magazines and Info Sites

http://www.mdreport.com/

Video Electronics Standards Association (VESA): http://www.vesa.org/

The TFCG group is a research group in the department ELIS at the University of Gent in Belgium. It is involved in several research topics, situated mainly in interconnection technology and microdisplays.

http://www.elis.rug.ac.be/ELISgroups/tfcg/index.html

DATA SHEET III-11.4. VARIABLE ADDRESSABILITY IMAGING SYSTEMS

Developing Critical Technology Parameter	Current night-vision sensors have an inadequate number of pixels to create high-quality images over a large field of view. Visible image-intensifier sensors with about 1 M pixels can provide the equivalent of 20/50 vision over a 30 × 40 deg field of view. IR sensors with about 76 K pixels can provide the equivalent of 20/150 vision over the same field of view. As the required field of view increases by 2–4 times in the next 15 years, the image quality becomes even worse. Trends in sensor development show an increase in pixel count over the next 10 years, but not at an acceptable rate. In addition, a special class of optical systems (variable resolution addressability optical sytems) that can use the available sensor pixels more efficiently, thereby simultaneously increasing the image quality and the field of view, needs to be developed.
Critical Materials	The system requires a precise, aspheric optical element made of glass or plastic.
Unique Test, Production, Inspection Equipment	The aspheric elements are small and have a large, but precise, variation in surface figure that cannot be measured on existing surface profilometers. Special techniques will need to be developed to inspect these optical elements.
Unique Software	Special figures of merit for optimizing high-distortion optical systems must be developed for use with commercially available lens design programs.
Technical Issues	The variable addressibility technology effectively reduced the number of image sensor pixels that are needed in a visual optical system by taking advantage of the variable acuity across the field of view of the eye. Needed is at least a 10× decrease in the number of image sensor pixels by using variable addressibility. Hence, image quality, as well as field of view, must be improved compared to current, conventional technology. Because fewer pixel means less data, the technology offers image data compression as well. Compactness and simplicity of optical design. Optimum pixel distribution for various applications. Human factors associated with using variable addressability systems. Improvement of task performance when using variable addressability system compared with constant addressability system. Extension to creation of programmable, dynamic, pixel allocation. Extension to coupling of eyetracking to pixel allocation.
Major Commercial Applications	Electronic binoculars. Night-vision viewers. Robot vision and inspection systems. Head-worn displays.
Affordability	Variable addressiblity promises to achieve (1) the performance of an expensive, large-image sensor using a commodity-priced, small-image sensor, thus enabling high-volume applications that are cost sensitive, and (2) the performance of an extremely large-image sensor that does not yet exist. Because variable addressability allows the use of a smaller image sensor, there is also an improvement in size and weight of the sensor. For head-mounted sensors, this may be a significant, enabling advantage.

RATIONALE

Advantages of Variable Addressability Night Vision Systems

- Enables high-quality night-vision systems without need for extremely large pixel image sensors.
- Smaller image sensor allows smaller and lighter night-vision system, which are more suitable for the user to wear.
- Smaller image sensor is less expensive and easier to manufacture.
- Fewer pixels means less data to handle for transmission and storage.
- Pixel distribution can be matched to different applications by using different lenses with the same image sensor.

There is an increasing need for night vision systems using visible and IR sensors that have larger fields of view and improved image quality. In 1999, both image quality and field of view are severely limited by the relatively small sensor arrays currently available (about 576 × 1414 for visible and about 240 × 320 for IR). In fact, neither of these sensors can provide the user with a 20/20 equivalent view of the world. At a 30 × 40 deg field of view, the visible sensor is 20/46 at best, and the IR sensor is only 20/150.

The pixel count of sensors is increasing, but not at a fast enough rate to meet the demand. As the field-of-view requirement increases to 60 × 80 deg and the required visual quality to 20/20 by 2008, there needs to be 17M pixels in the image sensor if conventional approaches are still used. This is nearly 20 times the size of night-vision sensors available today. Fortunately, there is a new technology that uses pixels in a more economical manner—variable addresssability. With variable addressability, the most pixels are placed where they can do the most good, namely in the center of the visual field of view. For head-mounted sensor applications where the user moves the head to scan a scene, variable addressability gives the user a high number of pixels at the center of the field, and fewer pixels at the edge of the field where the user's visual acuity is less.

By redistributing pixels to where they are needed, there are significant benefits. First, a smaller number of pixels on the sensor means a smaller, less expensive, lighter, and more manufacturable image sensor. Second, with fewer pixels there is less data to handle, which simplifies data storage and transmission. Third, custom pixel distributions can be created by using different lenses with the same image sensor.

WORLDWIDE TECHNOLOGY ASSESSMENT

Canada	●	China	●	France	●	Germany	●
Israel	●	Japan	●	Russia	●	Sweden	●
Switzerland	●	UK	●	United States	●●●		

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

This technology appears to be a unique concept under investigation at the University of Colorado, Boulder, in the Optoelectronic Computing Systems Center. The other nations have basic capability in conventional night-vision system display technology.

DATA SHEET III-11.4. ATMOSPHERIC PROBES IN THE 50–800 μm REGION OF THE SPECTRUM FOR POLLUTION AND NUCLEAR WEAPONS TEST DETECTION

Developing Critical Technology Parameter	This technology will provide the capability of probing the atmosphere in the terahertz spectral range (50–800 μm) for the presence of signature chemicals produced by nuclear explosions, chemical or biological weapons, and other atmospheric pollutants. The key to this effort is the development and use of unique, tunable, high-power, very narrow bandwidth FEL light to the study of the spectroscopy of the atmosphere in the terahertz range. Preliminary modeling of the atmospheric absorption suggests that many windows that will allow remote sensing of atmospheric pollutants exist in the terahertz range. In addition, studies can reveal the potential for identifying isotopically distinct compounds that may result from nuclear explosions.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	50–800 μm, continuously tunable FELs. Terahertz spectroscopic instrumentation and atmosphere simulation facilities.
Unique Software	Expanded data base for such programs as HITRAN as well as refined spectral modeling.
Technical Issues	Technical issues include FEL upgrades; terahertz high-resolution spectroscopy facilities and innovations; refined models of the spectra of expected pollutants and nuclear explosion products; and upgraded atmospheric data bases. Commercialization requires further development for military applications in the areas of FELs, spectral models, terahertz spectroscopy facilities development, and atmospheric modeling that are demanded by military applications but will be used by commercial applications.
Major Commercial Applications	Pollution monitoring, acid rain source detection, and greenhouse gas studies are a few of the applications that will drive this refined atmospheric pollution detection technology.
Affordability	When solid-state sources are developed to probe specific pollutants the technology will be affordable. The research is essential to this technology, it is essential to the military, and it will have significant nonmilitary payoffs.

RATIONALE

The technology of studying the atmosphere in the 50–800 μm region with extremely high spectral resolution will enable rapid detection of nuclear explosion and the use of chemical and biological weapons, and it will provide early warnings to the military of such events. It can do so by using the precisely tunable, very narrow band emission from FELs to probe this spectral region in the many windows that exist. Further, it will identify means to detect specific pollutants and provide data for modeling the atmosphere in designing terahertz probe systems. It provides a new means of examining the atmosphere and a means of detecting contaminants.

WORLDWIDE TECHNOLOGY ASSESSMENT

Germany ●●● Switzerland ●● United States ●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

These countries have been identified as conducting research programs in detection of pollution, but none appear to be concentrating on this wavelength region or the use of a FEL as a source for collection of data. Within the United States, NASA has major related programs, but none have been identified in this wavelength region. Most concentrate on airborne or spaceborne probes.

MODIS Atmosphere Overview

http://modarch.gsfc.nasa.gov/MODIS/ATM/modatm.html

NASA JPL Program, Airborne Visible/Infrared Imaging Spectrometer (AVIRIS)

http://makalu.jpl.nasa.gov/docs/workshops/98_docs/toc.htm

Airborne Imaging Spectrometry at DLR, German Aerospace Center

http://atlas.op.dlr.de/dais/dais.htm

Remote Sensing Applications Division, Department of Geography, University of Zurich

http://www.geo.unizh.ch/~dschlapf/tracegas.html

BACKGROUND

Because the resources to conduct this study exist at the School of Optics/CREOL at the University of Central Florida (FEL and spectroscopy), the University of Hawaii (FEL at higher frequencies), the University of Alaska (atmospheric range), and the University of South Florida (atmospheric spectroscopy and LADAR), it is likely that the results necessary to identify appropriate target pollutants can be obtained in the 5-year time frame. As such compounds are identified, research towards solid-state laser sources to probe specific compounds will be started.

DATA SHEET III-11.4. TWO- AND THREE-DIMENSIONAL, OPTICALLY WRITTEN, REAL-TIME DISPLAYS

Developing Critical Technology Parameter	Materials that can be excited by two photon processes to emit visible light and that can be dispersed as particles within a passive host are dye doped plastics and rare earth doped fluorides. We can optimize the particles for emitting red, green, and blue light and then place them throughout a medium. This approach allows us to form monochromatic or polychromatic displays in both 2– and 3–D versions of any desired size and shape. Parallel to the materials research and spectroscopy, modulators and scanners for the light to address the necessary locations in the display are being developed.
Critical Materials	Studies are necessary to identify the optimized red, green, and blue emitters for two-photon or two-step absorption excitation, which then must be prepared in particle form. Particle size and density in the host medium must be selected. The host medium will be an optical plastic allowing for any desired size and shape. The materials studied as potential emitters include dye doped plastics, rare earth doped fluorides, and other crystalline or glass hosts.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	While this technology is developed into actual 2– and 3–D displays, software will have to be developed or adapted to drive the scanners to address the necessary pixels or voxels in the display medium with the necessary scan speeds and accuracy.
Technical Issues	This technology will compete with existing video, LCD, LED, and plasma displays. Unlike these others, this technology has the potential to provide 3–D and 2–D displays of virtually any size and shape. The issues influencing the development of this technology are identifying optimized red, green, and blue emitters, identifying selective excitation processes for each type of emitter, preparing emitting particle host combinations that have least scatter, designing modulators and scanners compatible with the demands of the desired displays, and integration of these issues with software into true 2– and 3–D displays. This technology requires optical scientists and technicians as well as engineers versed in display technologies. The technology is not yet commercially developed. Thus, it can be developed for military uses in specific versions that meet military demands.
Major Commercial Applications	Commercial applications range from small, head-mounted, transparent displays for physicians, machine operators, drivers, pilots, and maintenance workers to windscreen displays in autos and aircraft, to 3–D displays for air traffic control, product design, and engineering.
Affordability	Not an issue.

RATIONALE

The technology of optically written, real-time 2– and 3–D displays will provide superior, lightweight, conformable displays employing inexpensive display media (emitting particles dispersed in plastic hosts) and diode laser excitation sources. When the research and development stage is finished, the cost of 2–D versions of these displays will be competitive with and perhaps less than other types of displays. With proper opto-mechanical engineering, displays of this sort can be developed for head-mounted applications, windscreen displays, and 3–D displays in air traffic control, medicine, and engineering applications. No other display technology can produce true, real-time 3–D images, so cost comparison is not relevant.

This technology will lead to lightweight, inexpensive multicolor displays. It is based on optical, two-photon or two-step absorption in specially prepared materials that then emit visible light. It will make possible head-mounted and conformable windscreen displays that are transparent and rugged. Further, it will make possible for the first time multicolor, real-time, 3–D displays for the management of 3–D problems. These include the battlefield, military and civilian air traffic control, space and spacecraft management, and medical training and treatment, to name just a few. The development of display materials and systems for 3–D systems also makes possible 2–D displays having unique and useful features.

The advent of powerful, reliable, inexpensive diode lasers in the near IR makes possible development of a new display technology. The light from such lasers can be absorbed by many materials through either two-photon or two-step processes to excited states that can emit visible light. The concept of using such two-photon absorption to excite visible light emission in a display was suggested nearly 30 years ago. Unfortunately, the light sources, materials, and beam-handling optics were not available until now. Research efforts in the 1990's resulted in 3–D displays of limited size, color content, and spatial resolution. These employed (1) rare earth doped chalcogenide glasses or (2) rotating helices as display media. In the first case, they are severely limited in size, and in the second, the limitation is that of a mechanically moving display medium.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●●	Canada	●●	China	●	France	●●●
Germany	●●●	Israel	●●	Japan	●●●●	Russia	●●●
South Korea	●●	Sweden	●	Switzerland	●●	Taiwan	●●
UK	●●	United States	●●●●				

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Display technology is underway throughout the industrialized world.

DATA SHEET III-11.4. ADVANCED OPTICAL SENSING TECHNOLOGY

Developing Critical Technology Parameter	There are outstanding problems associated with atmospheric imaging over long paths in the presence of particulates, aerosols, and turbulence for both visible and IR detection, identification, quantification. Combustion products, solid propellants, and particulate emissions of different origins are only several other examples where structural characterization requires optical-based instruments and techniques that allow on site or remote, continuous measures without sampling. Particulate matter monitoring could become especially important because of the evolution of new environmental standards. Another area where a particulate description of the media is appropriate includes underwater imaging and special operations involving the interaction of light with the ocean, including ocean boundaries (sea surface and ocean floor) and the specific atmosphere within tens of meters of the ocean surface.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Technical Issues	Further development should be based on improved understanding of wave progation and scattering phenomena: • Novel design for imaging (scattering) techniques; • New photon sources and detection systems with specific time, polarization, and wavelength properties; and • New image assessment, enhancement, and pattern-recognition methods that account for quantitative aspects of multiple-scattering contributions.
Major Commercial Applications	Remote, real-time metrology and diagnostic technologies are crucial in all the technological applications associated with particulate systems. Particulate systems as a core technology affect advanced material, chemical, pharmaceutical, ceramic powder, pesticide, paper, cosmetic, and environmental industries, among others. The unavailability of on-line analysis, monitoring, and control methods determines a lack of knowledge on structural properties of dense systems and prevents efficient processing and utilization of particulate systems. Noninvasive determination of structural aspects in biological tissues is crucial for a variety of *diagnostic* and *radiation delivery* applications. To directly probe microscopic properties of tissues, a particulate description, where components such as particles, fibers, macromolecules, and cells act as individual scattering centers, is needed. Biological tissues can be described as particulate systems, but the inhomogeneity, multilayered structure, and anisotropy make their characterization a challenging task. There is also another aspect that makes light scattering appealing for diagnostic applications. Unlike X ray and magnetic resonance imaging, which utilize very short or very long radiation wavelengths in comparison with typical scale lengths to be investigated, optical methods probe an intermediate frequency regime that facilitates detection of metabolic abnormalities leading to tumor formation. This distinguishes the optical methods from their counterparts that respond to structural damage resulting from abnormal metabolism.
Affordability	Not an issue.

RATIONALE

There are many outstanding problems associated with atmospheric imaging over long paths in the presence of particulates, aerosols, and turbulence for both visible and IR detection, identification, and quantification. This technology addresses many of those outstanding issues.

Combustion products, solid propellants, and particulate emissions of different origins are only several examples where structural characterization requires optical-based instruments and techniques that allow on-site or remote, continuous measures without sampling. Particulate-matter monitoring could be come especially important because of the evolution of new environmental standards. The military needs this technology to determine various exhaust products, which helps identify the type of vehicle being used. It can also lend itself to identifying rocket- and missile-plume emissions.

Another area where a particulate description of the media is appropriate includes underwater imaging and special operations involving the interaction of light with the ocean, including ocean boundaries (sea surface and ocean floor) and the specific atmosphere within tens of meters of the ocean surface.

WORLDWIDE TECHNOLOGY ASSESSMENT

China	●●	France	●●	Germany	●●	Israel	●
Japan	●●	Norway	●	Russia	●●	South Korea	●
Sweden	●	Taiwan	●	UK	●	United States	●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The United States has the largest programs.

DATA SHEET III-11.4. PASSIVE OPTICAL LIMITING

<table>
<tr><td>Developing Critical Technology Parameter</td><td>
Passive optical limiting is a means of protecting eyes and other optical sensors from laser damage. Although fixed-line filters can be used for known threat laser wavelengths, they are not a solution for tunable lasers. Active switches are expensive and too slow for many pulsed-laser threats. NLO materials offer a low-cost and wavelength-agile method to block high-intensity lasers by nonlinear absorption, nonlinear refraction, or nonlinear scattering.
Materials with high broadband linear transmittance over this range (see table) while clamping transmitted energy below 1 μJ in the worst case—preferably below 0.1 μJ for eye protection—are needed and must work for multiple threat lasers
<table>
<tr><th colspan="4">Limiters for nanosecond pulsed lasers</th></tr>
<tr><th>Parameter</th><th>1999</th><th>Projected by 2005</th><th>Nature's Limit</th></tr>
<tr><td>Max. Transmitted energy (μJ)</td><td>0.5</td><td>0.1</td><td>N/A</td></tr>
<tr><td>Transmission bandwidth (nm)</td><td>100</td><td>200</td><td>N/A</td></tr>
<tr><td>Photopic transmittance</td><td>25%</td><td>50%</td><td>N/A</td></tr>
<tr><td>Damage threshold (mJ)</td><td>5 mJ</td><td>50 mJ</td><td>N/A</td></tr>
</table>
</td></tr>
<tr><td>Critical Materials</td><td>Organic reverse-saturable absorber and two-photon dyes, carbon-particle suspensions, and copper chloride. Material must have high damage threshold.</td></tr>
<tr><td>Unique Test, Production, Inspection Equipment</td><td>None identified.</td></tr>
<tr><td>Unique Software</td><td>Modeling software is required for the design and optimization of devices. This is in an advanced state of development for dyes, but not for suspensions. None identified.</td></tr>
<tr><td>Technical Issues</td><td>
Single materials do not exhibit large enough limiting properties over a sufficiently broad bandwidth to provide protection combined with large transmittance over the visible spectrum and good color vision. Ways to make suitable mixtures of materials and encapsulate them in stable, solid-state hosts are required. A predictive capability for the excited state absorption of dyes is needed.
Nonlinear effects are small enough to require that the nonlinear material is in a focal plane to provide sufficient energy density. This means an intermediate focal plane is needed. This is fine for sensors, sights, binoculars, etc., but for bare eye protection, goggles with intermediate focal plane are needed.
Nonlinear materials must have high damage threshold. Typically, nonlinear materials have low damage thresholds, but “tandem” designs can greatly increase thresholds. When a device is damaged, it must be fail-safe, that is, become opaque in the damaged spot.
</td></tr>
<tr><td>Major Commercial Applications</td><td>Eye protection against industrial accidental exposure.</td></tr>
<tr><td>Affordability</td><td>Passive systems are much less expensive than active switches. Materials are generally inexpensive. One issue is the cost of possible redesign of systems to incorporate protection.</td></tr>
</table>

RATIONALE

Military applications include eye protection for soldiers, pilots, sights, and periscopes. Sensor protection requirements are for the visible, near-IR (600–900 nm), and mid-IR (1–12 μm) wavelengths.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●●	Canada	●	China	●●	France	●●●
Germany	●●	India	●	Israel	●●	Japan	●
Netherlands	●	Norway	●	Russia	●●	Singapore	●
South Korea	●	Sweden	●	Taiwan	●	Ukraine	●
UK	●●●	United States	●●●●				

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Research in this area is conducted in many nations. Selected references follow.

Optical Limiting References

United States

Tran, Phuc, "Optical Limiting and Switching of Short Pulses Using a Non-Linear Photonic Band Gap Structure with a Defect," NAWC, China Lake, *JOSA B*, October 1997

Abstract: An extension of the recently introduced nonlinear finite-difference time-domain (NFDTD) technique [P. Tran, *Optics Letts.* **21**, 1138–1140 (1996)], for the study of electromagnetic wave propagation in a nonlinear Kerr medium, to include absorption, is presented. Theoptical limiting and switching of short pulses using a nonlinear quarter-wave reflector (a one-dimensional photonic bandgap structure) with a defect is studied. Comparison with an optical limiter and an optical switch using a perfect nonlinear quarter-wave reflector shows that introducing a defect can improve the performance of these devices.

The Army awarded nine Phase II contracts from FY97 STTR Program. GELTECH, INC Optical Limiting Windows for Eye and Sensor Protection from Laser Radiation.

Perry, Joseph J., et al., "Enhanced Reverse Saturable Absorption and Optical Limiting in Heavy-Atom Substituted Phthalocyanines," Jet Propulsion Laboratory, California Institute of Technology.

Japan

TOYOTO CROL

"Optical Limiting Property of Fullerene-containing Polystyrene," *J. Mater. Sci. Lett.*, 16 (1997), 2029–2031

"Second-Order Optical Nonlinearity of Urethane-Urea Copolymers: Influence of Main-Chain Structure," *Jpn. J. Appl. Phys.* Part 1, 36–9A (1997), 5518–5522.

Reprints of the papers are available upon request. Please send request e-mail to revank@mosk.tytlabs.co.jp.

Australia

The Australian National University, Canberra, ACT 0200

Organometallic Materials

The Organometallics Materials group is interested in the synthesis, structure, bonding, reactivity, and physical properties of organometallic materials, specifically those with a transition metal-carbon bond. At present, major foci of research are the chemistry of metal cluster complexes and the NLO properties of organometallic complexes. The Group is headed by Dr. Mark Humphrey.

UK

"Refractive Nonlinearity of Novel Molecular Materials"

Professor D.D.C. Bradley, Department of Physics and Centre for Molecular Materials, Sheffield University, Hicks Building, Hounsfield Road, Sheffield, S3 7RH.

Professor A.E. Underhill, Department of Chemistry, UCNW, Bangor, Gwynedd, LL57 2UW.

Abstract: These showed a very large reverse saturable absorption response which gives an optical limiter performance that is very promising for application.

Switzerland

Prof. Dr. Fritz K. Kneubühl (emeritus), "Time-dependent Optical Limiting of Laser Pulses by Thermal Lensing and Kerr Nonlinearity in CS2," ETH, Zurich.

Abstract: Passive optical limiters with various materials and lasers are of wide interest, i.e., for protection of laser optics, human eye protection, or as power limiters when inserted inside the laser cavities. We have investigated such an optical limiting device consisting of a CS2 filled vessel with our pulsed TEA CO2-laser system. The limiting characteristic depends on the pulse duration of the incoming laser radiation. For laser pulses which are much shorter than the built-up time for a thermal density change, focusing through Kerr nonlinearity dominates. Pulses that are longer than this built-up time are influenced by the thermal defocusing which exceeds the effect of focusing by an order of magnitude. We have shown that the device of optical limiting can also be applied to perform various beam shaping. Thus, we can control the pulse duration by simply placing the limiting sample into the proper position. We have also demonstrated for the first time the use of an optical limiting device for the production of pulses with cw-lasers. Finally, we have succeeded to formulate a simple theoretical approach which gives a good quantitative agreement with the experimental results. This agreement is equal to that of previous sophisticated theories.

Contacts: M.O. Baumgartner, D.P. Scherrer, F.K. Kneubühl.

See also:

http://www.iqe.ethz.ch/irp/Welcome.html

http://www.iqe.ethz.ch/irp/office/PhoneList.html

Germany

"Modeling of Picosecond-Pulse Propagation for Optical Limiting Applications in the Visible Spectrum," S. Hughes, J.M. Burzler, and T. Kobayashi.

J.Burzler@Physik.TU-Chemnitz.de

Abstract: Efficient beam propagation methods are employed to model, quantitively, the roles of internal and extental propagation effects from the optical limiting materials, zinc selenide and chloroaluminium phthalocyanine. By exploiting the nonlinear absorptive and refractive nonlinearities, excellent optical limiting behaviour is demonstrated at 532 nm, provided that sufficient sample thickness can be accommodated.

Journal: *Journal of the Optical Society of America B*, Vol. 14, No, 11, pp. 2925–2929 (1997).

DATA SHEET III-11.4. LASER REFRIGERATION BY MEANS OF MOLECULAR COOLING

Developing Critical Technology Parameter	Ultracold Molecules can be formed by means of lasers using coherent state-selected beams of molecules formed from Bose-Einstein condensates (BEC). Developing techniques to produce molecules in this low vibrational state to form ultracold refrigeration is the long-term goal. Laser photoassociation has achieved molecular cooling to 300 µK within no cryosources. Colliding pairs of these cold molecules form only one vibrational energy state. Development of this technology requires generating a database for BEC statistics and determining which molecules have the greatest potential to be cooled under laser radiation.
Critical Materials	None critical—materials such as potassium can be used to trap and cool the molecules (to less than 10^{-6} K).
Unique Test, Production, Inspection Equipment	Optical spectroscopic methods need to be developed for both the destructive and nondestructive characterization of ultracold molecular samples.
Unique Software	None identified.
Technical Issues	Cooling of alkali metal molecules has been produced using near-IR lasers. The extension of this technique to other molecules will require a narrowband visible or UV laser.
Major Commercial Applications	Commercial applications are speculative at this point; however, two such applications are refrigeration or quantum computing in which an optical lattice is developed where two state-selected atoms can be converted into a single state-selected molecule or an atom-molecules superposition state.
Affordability	Affordability is speculative at this point although costs of BEC are decreasing rapidly.

RATIONALE

The ability to cool a small area within a microchip or computer chip will become increasingly important in the near future for both commercial and military systems. This technology of using BECs is developing techniques and the process and procedures necessary to produce very low-temperature molecules by means of laser radiation.

WORLDWIDE TECHNOLOGY ASSESSMENT

United States ●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The concept is being studied at the University of Connecticut, Photonics Research Center. No similar work has been identified elsewhere.

DATA SHEET III-11.4. VARIABLE WAVELENGTH IMAGING SPECTROMETERS

Developing Critical Technology Parameter	The technology required to image different wavelength intervals of interest in subsequent planes within an imaging cube FPA is emerging. Each volume pixel (Voxel) is associated with an x, y coordinate and a different wavelength interval in the z direction. This is done without scanning in the Mooney-Descour imaging spectrometer. The key is the dispersing element used in form of the 3–D FPA.
Critical Materials	High resolution 10,000 × 10,000 FPA.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Technical Issues	Fabrication of grating pattern in situ or via LCD to exact tolerances.
Major Commercial Applications	Many applications could use a high-resolution FPA.
Affordability	Cost must be reduced from the current high-resolution FPAs. This new technology should lead to significant cost reduction over current designs.

RATIONALE

High-resolution images taken simultaneously with discrete wavelength intervals (typically 10–20 bands) is possible. This technology is required to discern camouflage material and paint from organic and background materials. Since camouflage and paint typically have absorption spectra that are distinct and different from that of organic materials, it is important to be able to image in different wavelength bands and look at image differences. This technology has the potential of providing this information and processing it so that many variations of the data can be reviewed from many different applications.

WORLDWIDE TECHNOLOGY ASSESSMENT

Canada	●	China	●●●	France	●●	Germany	●
Israel	●	Japan	●●●	Netherlands	●	Russia	●
Singapore	●	Sweden	●●	Switzerland	●●●	Taiwan	●
UK	●●	United States	●●●				

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The United States, China, Japan, and Switzerland have significant R&D related to imaging spectrometers. The technologies covered here are under investigation at the University of Arizona, Optical Sciences Center. The concept requires very complex focal plane arrays—an area where the United States is a world leader.

DATA SHEET III-11.4. MEMS AND FPA ADAPTIVE OPTICS

Developing Critical Technology Parameter	The ability to control the phase of a propagating optical wave front is a key enabling technology for a host of scientific, commercial, medical, and defense applications. By controlling the phase of a propagating beam it is possible to correct aberrations in optical systems, control the shape of a focused laser beam, and even redirect the laser beam. Scientific and defense applications include high-speed optical wave-front control for correcting atmospheric turbulence effects for astronomy, space surveillance to provide higher resolution imagery, and control of fixed aberrations in optical systems to allow the development of simpler lens and mirror arrangements.
Critical Materials	Silicon and associated semiconductor materials and processes.
Unique Test, Production, Inspection Equipment	Test/inspection equipment capable of operating 2–D optical MEMS arrays to measure such parameters as input/output power and component alignment. Computerized driver equipment capable of controlling hundreds or thousands of microactuator channels in real time.
Unique Software	Optical simulation software.
Technical Issues	Development of fundamental MEMS science for high optical power applications. Development of packaging of MEMS devices for high optical power applications. Understanding of the performance of MEMS for optical power handling ability, dynamic range, frequency response, and beam-shaping characteristics.
Major Commercial Applications	HDTV, solid-state device focus control for camcorders, and beam-quality control for line-of-sight laser communications; optical interconnects between high-speed electronic modules. Medical applications for optical wave-front control technology as related to laser eye surgery.
Affordability	The bottleneck now is in not having affordable fast computers capable of controlling thousands of channels in real time.

RATIONALE

The ability to control the phase of a propagating optical wave front has significant defense applications, as well as commercial applications. The use of MEMS technology is making optical phase control practical. Correcting aberrations has application to optical communications and to imaging and focus control. The technology permits the use of optical correlation with application to target acquisition. Laser beams can be steered and focused to improve target tracking and displays.

WORLDWIDE TECHNOLOGY ASSESSMENT

United States ●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The concept is based on R&D under way at the University of Colorado, Boulder, NSF Center for Advanced Manufacturing (CAMPmode). MEMS R&D is extensive throughout the industrial world, but this is a specific area of investigation.

DATA SHEET III-11.4. DISPLAYS FOR WEARABLE COMPUTERS

Developing Critical Technology Parameter	Wearable displays are rapidly evolving as a result of recent progress in new approaches, as well as evolving technologies such as diffractive and aspherics optics. Specifically, novel technologies to be applied to wearable computers include eyetracking capability; multiple focus to avoid conflicts of accommodation and convergence; and projection optics that allow for small, compact, and lightweight devices. Critical technical parameters: (see table below)
Critical Materials	A critical technology required for wearable computers is microretroreflective material, which comes in sheets. Currently, microprisms or microbeads are sold by 3M and Reflexite Technology. The technology parameters are, however, not optimized for imaging applications. New developments in retroreflective material must be initiated for applications to imaging. Ultimately, desirable properties of the material are optimally sized microstructures, zero observation angle, and minimization of ghost images via proposed approaches. Moreover, new material for miniature low-cost displays should be investigated.
Unique Test, Production, Inspection Equipment	None identified at this time.
Unique Software	Ability to generate true stereoscopic images based on interpupillary distance of the user. Virtual worlds or augmented reality environments.
Technical Issues	Miniaturizing the optics. Requires developing retroreflective sheeting material that has properties for imaging applications (Hua et al., AO2000; ODALab/UCF). Requires developing high-resolution 5–10 µm pixels miniature color flat-panel display types of about 1–1.5 in. diagonal; optically written displays? Eyetracking integration in head-mounted devices is ultimately required. The commercial technology requires further development for military applications(s), including eyetracking integration. (above).
Major Commercial Applications	Personal display, wearable computers, teleconferencing, remote teaching, telemedicine, surgical display aids, teleconferencing, remote teaching, training systems, vehicular heads-up displays, and aircraft displays.

Projected Head-Mounted Displays

Parameter	1999	Projected by 2010
FOV (degree)	30–40	80–90
Weight (g)	1000	20–250
Ergonomy	nonoptimized	eyeglass type
Brightness	1–2 FL	50–100 FL
Image Quality	no MTF at 101p/mm	limited by visual acuity
Eyetracking Capability	No	Yes

Affordability	Technology can be commercialized because of the low cost of the miniature optics and retroreflective material compared to computer automatic virtual environment (CAVE) types of environments.

RATIONALE

Because of the new capability to miniaturize the optics, projection lenses for 3–D displays may be designed to be head mounted, suppressing the need for multiple high-cost projection lenses (e.g., Barcos) placed in a room as found in CAVE environments. Thus, there is no need to calibrate the multiple projection lenses and no need to set the overall CAVE-type environment. Sheeting material positioned in a few seconds can serve as a projection screen. This technology is portable, quickly set up and removed; it may be created at low cost. Sheeting material such as provided by 3M and Reflexite technology is very inexpensive (~ $1/m^2). This technology will strongly compete with CAVE-type systems or provide substitutes for a large spread of such 3–D visualization environment when less than immersive field of views are required.

Among several approaches, optical see-through technologies have the highest potential because they can ensure safety of the user. Also, hybrid optical/video see-through where video input is used to either measure the distance and orientation of objects in the scene or to capture information that can be used to enhance the real scene (e.g., IR camera recording) will play critical roles in new developments of the technology.

Among optical see-through technologies, a novel approach to miniature displays is projective head-mounted displays. In projective displays, the optics are equivalent to projection optics (rather than magnifier optics). The key difference is the ability to correct optical distortions, as well as other optical aberrations, a critical component related to miniaturizing the technology.

Furthermore, it has been established in the literature (Rolland et al., AO 2000) that multifocus devices are required to minimize conflicts of acommodation and convergence in head-mounted displays. So novel technologies providing multiple focus will need to be conceived.

Also, eyetracking integration reveals the importance of head-mounted displays. Eyetracking capability can be used as an input device (hands-free operation), as well as an assessment tool to investigate how such systems are used.

By 2005, projections indicate that devices using projection optics will become ultralightweight, similar to eyeglasses but with large FOVs (e.g., 70 deg). Such devices are attractive to the military because they can be used outdoors. Military applications include portable displays for the battlefield; aircraft displays; 3–D displays; and visualization for military planning, rehearsing, and debriefing; soldier support environment/display/remote communication; soldier kit, including medical data quickly visualized in case of emergency; teleconferencing; and training systems. Drivers are teleconferencing and training systems. These devices also have nonmilitary applications in creating collaborative environments, telemedecine, teleconferencing, remote teaching, training systems, and 3–D visualization.

There are no special requirements such as a cooperative agreement or vehicle for the U.S. Government to gain access to this technology.

WORLDWIDE TECHNOLOGY ASSESSMENT

China	●●	France	●●	Germany	●●	Israel	●
Japan	●●	Norway	●	Russia	●●	South Korea	●
Sweden	●	Taiwan	●	UK	●	United States	●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

There is considerable commercial activity in wearable computers. China, Japan, France, Germany, and Russia have moderate R&D programs underway. The United States has significant R&D in progress. This particular data sheet describes programs with military potential.

SECTION 11.5—OPTOELECTRONIC AND PHOTONICS TECHNOLOGY

Highlights

- Micro-optics will begin complementing and then replacing electronic components on chips, reducing heat and improving speed and throughput, while reducing cost.
- Nanotechnology will result in significant improvement in electro-optic and NLO devices, which will have widespread military applications
- The use of optoelectronics technology in military applications has a number of advantages over classical electronic technology. Among these are radiation hardening, greater bandwidth, lower power consumption, reduced size/weight/volume, electromagnetic interference/electromagnetic compatibility (EMI/EMC) considerations, and memory size.
- Photonics is a major developing technology within DoD.

OVERVIEW

Note that the term "optoelectronics" is typically used to describe devices and components (hardware) that respond electrically to photons, whereas the term "electro-optics" is typically understood to be the science of the relationship between electricity and optics. Optoelectronic devices can be regarded as the set of devices and components used to implement a variety of military, industrial, and consumer photonics applications. Optoelectronic devices are also used extensively to interconnect the photonic and electronic domains. The *Photonics Dictionary* defines optoelectronics as:

> Pertaining to a device that responds to optical power, emits or modifies optical radiation, or utilizes optical radiation for its internal operation. It relates to any device that functions as an electrical-to-optical or optical-to-electrical transducer. Electro-optics is often erroneously used as a synonym.

Photonics applications have been considered for many years. Applications have been limited; however, DoD now has a major thrust underway to introduce photonics applications into a number of existing or new military applications. Industrial and consumer applications are also being considered. The *Photonics Dictionary* defines photonics as:

> The technology of generating and harnessing light and other forms of radiant energy whose quantum unit is the photon. The science includes light emission, transmission, deflection, amplification and detection by optical components and instruments, lasers and light sources, fiber-optics, electro-optics instrumentation, related hardware and electronics and sophisticated systems. The range of applications of photonics extends from energy generation to detection to communications and information processing.

DoD uses the following definition for photonics in program reviews:

> Concept for computing and data transmission using photons in place of electrons; pertaining to devices and systems that utilize photons instead of electrons for computational purposes and information transmission.[1]

Photonics generally involves the replacement of components or applications based on pure electronics with components or applications implemented with technology based on light wavelengths. Many of these components and applications exist or are under development in many military applications such as avionics, acoustic surveillance, radar, shipboard systems, space, land vehicles, and night vision. Some reports use the terms photonics or optoelectronics interchangeably—there is not yet universal agreement on the definitions.

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[1] "Photonics Pre-TARA Review," Working Group C, DoD Advisory Group on Electronic Devices (AGED), 29–30 January 1997.

A typical photonics application is the replacement of avionic “fly-by-wire” control systems with “fly-by-light.” Another application is interconnect technology for radar phased arrays.

Typical optoelectronic devices employ lasers (especially surface-emitting and edge-emitting semiconductor types), fiber-optics, detectors, and various optical signal-processing techniques. The use of MEMS technology is increasingly important in many of these devices

RATIONALE

This section provides a variety of applications and component developments that marry lasers and optics. Many are examples of the concept of optoelectronics—the art of combining the world of electronics with photons. Moving the base band for information transfer and processing from the gigahertz (GHz) region to the terahertz (THz) region results in a 2 to 3 orders of magnitude increase in available bandwidth and data transfer

The continual maturing of optical technologies has permitted a new focus, that of micro-optics technologies, which are now enabling complex systems to be constructed, such as spatial light modulators, integrated opto-electronic arrays, opto-electronics, and quantum optoelectronics at the chip level. In addition, fiber-optic components and systems represent an area in which commercial investment has led the way for DoD applications. Basic data-transmission systems have been adapted and improved for battlefield environments, with the commercial sector leading the technology development in areas such as wavelength diversity multiplexing (WDM) and time division multiplexing (TDM) using fiber-optic transmission lines. The use of fiber-optics on aircraft, satellites, ships, and submarines has started to expand, following similar commercial successes. This increased utility of fiber-optics along with optical imaging technologies and optical storage devices is pushing the technology envelope in related areas such as optical parametric amplifiers and NLO materials development for waveguide and switching applications in the micro-optics field.

The use of optoelectronic devices in military applications has a number of advantages over classical electronic technology. Among these are radiation hardening, greater bandwidth, lower power consumption, reduced size/weight/volume, improved EMI/EMC considerations, and greater memory size.

The primary applications include telecommunications, local and wide area networks, optical interconnections, and optical storage. The field of optoelectronics/photonics is exploding, and other applications can be expected to rapidly develop.

Optical sensors (electro-optical sensors) are covered in Section 17.5.

WORLDWIDE TECHNOLOGY ASSESSMENT

China	●●	France	●●	Germany	●●	Israel	●
Japan	●●●	Netherlands	●	Russia	●	Singapore	●
South Korea	●	Taiwan	●●	UK	●	United States	●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

A new center has been established at the George Mason University under the joint sponsorship of DARPA/MTO. Their mission statement:

> We are pleased to announce the formation of the Consortium for Optical and Optoelectronic Technologies in Computing (CO-OP). The CO-OP is expected to draw its membership from industry, universities and government agencies. The purpose of the CO-OP is to promote the development of optical and optoelectronic platform technologies by making them widely accessible and by a cooperative sharing of test data and design methodologies among the consortium members. The primary emphasis will be to work with the existing technologies rather than to work ON developing new technologies or improving their performance. In that regard, the purpose of the consortium is complementary to the already existing R&D efforts in technology development. The consortium is expected to facilitate the use of state-of-the-art optoelectronic devices in advanced systems and applications by making them easily accessible. We will determine the overall direction of the CO-OP in consultation with an advisory committee. The consortium will conduct its operations through an Administrative Office located at George Mason University in Fairfax, VA.

http://co-op.gmu.edu/

This is a potential platform for exploitation of the “Developing Technologies” identified in this section of the MCTP, when they are proven.

LIST OF TECHNOLOGY DATASHEETS
III- 11.5. OPTOELECTRONICS AND PHOTONICS TECHNOLOGY

The following developing technology is in the very early research phase, and numerical values and specific goals for some of the critical parameters have not yet been identified and/or determined at this time.

DATA SHEET III-11.5. COHERENT RF PHOTONIC PROCESSING FOR ADAPTIVE ARRAYS

Developing Critical Technology Parameter	Optimal signal processing for the receive mode of large, wideband phased-array antennas is enormously challenging, requiring petaFLOP computational throughputs. Appropriate coherent optical techniques incorporating true-time-delay and adaptive signal combination are required to solve this problem.
Critical Materials	Holographic adaptive-array processing requires either high-speed photorefractive materials for use with Broadband and Efficient Adaptive Method for TTD Array Processing (BEAMTAP) processors or cryogenically cooled photon-echo materials to operate as intrinsic true-time-delay processors. Finding materials compatible with all of the other system components represents a compromise in performance between the laser, modulators, detectors, and dynamic hologram. Time delay in a traveling-wave photoconductive detector (GaAs, Si, or SIC) is a critical requirement.
Unique Test, Production, Inspection Equipment	Antenna array processor testing requires generation of the broadband signals that would be received by such an array, and this presents an extraordinary challenge. The simulator for a single received signal is actually the same type of system used to produce the necessary signals required for true-time-delay transmit mode of operation, and simulating numerous signals is typically required.
Unique Software	The BEAMTAP algorithm has been implemented as an interactive data language (IDL) graphical user interface (GUI) for algorithm exploration, and it is amendable to a variety of scenarios. Numerous variants, including linear arrays, circular arrays, narrowband jammer nulling, broadband jammer nulling, beam steering, effects of element couplings, effects of modulation nonlinearities, and tradeoffs of spatial aperture vs. tapped-delay-line length, have been investigated using this software.
Technical Issues	Squint-free broadband operation requires time-delay-and-sum processing. Dynamic Range of 140 dB is only possible using coherent processing gain. Coherent fan-in allows efficient low noise figure operation. Algorithm convergence may be slow in presence of many strong jammers. Array topology can be arbitrary and in a dynamically varying space. Closed-loop adaptation senses component variability and compensates. Rapid control of array scanning required.
Major Commercial Applications	Large array processing finds application in DoD systems and in radio astronomy where systems are being envisioned with 1,000,000 elements. These systems will only be feasible using coherent optical processing.
Affordability	By utilizing parallel optical processing that scales to arbitrarily large arrays without increasing the processor complexity, the cost of processing arrays with 1,000 or more elements becomes manageable.

RATIONALE

The large number of parallel wideband channels that must be controlled and processed in RF antenna arrays presents an enormous signal-processing challenge for conventional digital techniques. The transmission of these RF signals from the antennas to the processor will inevitably use optical fiber, and by utilizing coherent optical processing of this arrray of signals cohered by dynamic holograms, least mean square (LMS) adaptive array processing can be implemented in real-time. The use of either BEAMTAP or photon echo processing enables these systems to accomplish broadband, true-time-delay, squint-free beamforming and jammer nulling. Such advanced, university-based, systems-oriented research can dramatically enhance critical mission capabilities and simultaneously alleviate requirements on the development of devices and components.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●	Canada	●	China	●	France	●●●
Germany	●	Japan	●●	Netherlands	●●●	Russia	●●●●
Taiwan	●	UK	●	United States	●●●		

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

DATA SHEET III-11.5. SILICON-BASED OPTICAL INTERCONNECTS

Developing Critical Technology Parameter	Source: Modulation speed (10 GHz), quantum efficiency (10 percent), lifetime (1×10^6 hours), power (>100 µW). Modulators: speed (10 GHz), power dissipation (<100 µW), modulation depth (>90 percent).
Critical Materials	Silicon-on-insulator (SOI) wafers. Very high purity starting materials.
Unique Test, Production, Inspection Equipment	None identified. All equipment should be standard semiconductor processing equipment.
Unique Software	Waveguide analysis and 2–D E/M modeling software.
Technical Issues	Materials compatibility, energy efficiency, device lifetime, and modulation speed.
Major Commercial Applications	SOI applications. Silicon-compatible integrated modulators and detectors. SiGe heterostructures.
Affordability	SOI technology has demonstrated that a $300–$400 increase in wafer cost increases the cost of the final processor by 10–15 percent. Thus, any proposed improvements should take final device cost into account.

RATIONALE

The use of silicon integrated circuits pervades defense and commercial communication as well as military weapons systems. For integrated circuits to continue to support the current requirements and become two to four times more dense in terms of computer power, optical interconnects and switches must become as ubiquitous as their electronic counterparts. While hybrid technologies (such as flip-chip bonded VCSEL arrays) may serve well in the interim, thermal management and reliability considerations suggest that the development of monolithic solutions needs to be addressed.

The steady reduction in electronic device size and increase in clock speed has led to a significant need for dense, high-speed, very large scale integration (VLSI)-compatible interconnect technologies. Two approaches for this are (1) silicon-based lightemitting devices and (2) silicon-based optical modulators. Devices based on emerging technologies such as SOI and copper metallization technologies are particularly critical.

WORLDWIDE TECHNOLOGY ASSESSMENT

Canada	●	China	●●	France	●	Germany	●●
Japan	●●	Russia	●	Sweden	●	UK	●●●
United States	●●●						

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The United States, as a world leader in semiconductor technology, is pursuing this technology very aggressively. It is key to greater performance. The other industrialized nations that are leaders in semiconductors also have substantial efforts.

DATA SHEET III-11.5. CHIP-LEVEL OPTICAL INTERCONNECTION

Developing Critical Technology Parameter	The need is for a family of low-cost (<$0.001/interconnect) optoelectronic chips that can form the building blocks for computing systems that are packaged either in 3–D stacks or as integrated wafers. A typical chip would contain hundreds of optical interconnects (OIs), each operating at several Gbits/sec, yielding a chip I/O rate >1 Tbit/sec. Optical crosstalk can be controlled by adding MEMS to maintain an alignment accuracy of the optical channels within 2 μm laterally and 5 μm longitudinally.
Critical Materials	Silicon and gallium arsenide wafers and other materials used in the microelectronics fabrication industry.
Unique Test, Production, Inspection Equipment	Test/inspection equipment capable of performing parallel measurements on operating 2–D optoelectronic arrays to measure such parameters as transceiver input/output power, component alignment, cross-talk between adjacent channels, channel bandwidths, and bit error rates.
Unique Software	Optical simulation software.
Technical Issues	Optical transmitters and receivers having lower power dissipation. Lower cost, integrated source and detector arrays. Lack of architectural knowledge on how to partition chip with existence of OI. Lower noise and higher gain detectors. Improved techniques for integrating optoelectronics (OE) with silicon chips. Need for packaging that is compatible with chip-level OI. Reduced OE power requirements so as to be compatible with Si power levels. Testability. Manufacturability (process compatibility with silicon and process scalability). Ability to easily establish and maintain alignment. Need for new optical models that can work for such small feature sizes.
Major Commercial Applications	High-performance parallel computers/switching systems for: High-resolution, real-time image processing (e.g., highly detailed operations in remote environments, maintaining worldwide databases on human demographics, and 3–D display). Image synthesis (e.g., entertainment/games and training with virtual environments). Multidimensional modeling and simulation (e.g., real-time weather prediction, DNA synthesis, electronic structure of macromolecules, world ecosystem modeling, and flow in porous media such as oil reserves). Video on demand.
Affordability	Orders of magnitude increase in computing throughput will reduce the required computing resources.

RATIONALE

Many processing algorithms important to DoD have high computational and communication requirements. One future design under consideration by DARPA calls for a 2–D FFT corner turn (between range processing and azimuth compression) for synthetic aperture radar (SAR) processors consisting of a 32 × 32 array of processors interconnected by a 64-bit wide network. This will require over 65,000 connections. For these connections, optical links with their 1 mW per link power requirements are far superior to electrical links with power requirements in the range of 60–100 mW per link.

The cost savings of interconnecting processing elements with a fully connected network, which optics can provide, rather than the partially connected networks, which electrically connected systems use, could be in the millions of dollars per system. This is because of the high cost of developing software for systems whose networks are running in excess of 50-percent utilization due to their partial connectivity. That is, the limitations of electronic networks lead to greater software development costs than for optical networks.

An appealing alternative to making larger and larger chips to address the need for more computational power is to provide optical interconnects between many smaller chips located in proximity to one another. Electrically interconnected multichip modules (MCMs) and 3–D chip stacks have been tried, but concerns exist regarding their cost competitiveness. MCMs require costly multilayer substrates to support the electrical interconnects, and a major cost factor for electrically interconnected chip stacks is the failure of the entire stack when a single chip fails. A focused effort in chip-level optical interconnection is needed to develop the enabling technologies for realizing a low-cost optoelectronic chip that can be used either in a cost-competitive wafer-based module or in a modular chip stack. The result will be a high-performance chip with terahertz I/O capability and with the ability to be packaged with many other chips in either a planar or stacked configuration. The cost savings promises to be significant.

WORLDWIDE TECHNOLOGY ASSESSMENT

Canada	●●●	China	●●	France	●●	Germany	●●
Israel	●●	Italy	●	Japan	●●●	Poland	●
Russia	●●	South Korea	●●	Sweden	●	Switzerland	●
Taiwan	●	UK	●●●	United States	●●●		

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

This technology is one of the keys to greater semiconductor device performance and is being emphasized strongly by most industrialized countries with semiconductor capability.

DATA SHEET III-11.5. OPTICAL PACKET SWITCHING

Developing Critical Technology Parameter	This technology applies to monolithic integrated all-optical and optoelectronic devices. This technology will enable very high speed processing and routing of very high frequency digital optical data trains. All-optical signal processing enables "on-the-fly" decoding of packet address information and routing of the packets to the designated destinations. Monolithic integration is key to making this technology viable for reliable, error-free operation. The ultrafast semiconductor all-optical and optoelectronic switches are useful for de-multiplexing 100-Gb/sec signals in TDM applications. They can be configured to perform automatic packet address decoding and packet routing of WDM packets with latency times less than twice the duration of the packet itself. The devices can also be easily configured for parallel interconnects for local area networks and computer backplanes running at a full 64-bit data bus. Packet switching of optical data at rates exceeding 1-G packets/sec assuming packet size between 128–256 bits.
Critical Materials	High-quality semiconductor quantum-sized structures including multiple quantum wells and multiple quantum dot materials. 6×6 optical space switch. Custom ASIC router control. Passive WDM components.
Unique Test, Production, Inspection Equipment	High-bandwidth electronic/optical interfaces. High-bandwidth bit error rate (BER) equipment.
Unique Software	Low-latency electronic host/network interface, not significantly different from existing software used to operate the current technology.
Technical Issues	Improvement of the energy required for switching. Issues with effects of residual free carriers than linger on long after the switching event. Reduction in cost of fabrication and packaging. Deflection routing protocol optimization. Scaling to large systems.
Major Commercial Applications	Future generation of very large bandwidth optical telecommunication networks with many WDM channels operating at 100 Gb/sec. Optical backplane interconnects for local network of very high performance computers and supercomputers. Optical internet protocol (IP) switching for backbone telecomm carriers. Distributed high-performance computing.
Affordability	Affordability must be addressed at all levels of development to provide DoD with logistic options.

RATIONALE

This technology will play a significant role in distributed radar data processing, distributed real-time battlefield command and control, and distributed high-performance computing. As this technology is developed, each of these will be significant to the military in the out years.

Monolithic, integrated, all-optical packet switches will be enablers for the ultimate in high-bandwidth optical telecommunications, as well as for local supercomputer networks. All-optical packet header address decoding removes a lot of the overhead penalty associated with traditional electronic packet switching.

The military will benefit strongly from the implementation of systems incorporating semiconductor all-optical switches. A network of computers interconnected via a parallel optical bus would run military software codes specifically written for parallel computing applications such as target recognition, missile course intercept calculations, and other remote targeting applications. Automatic optical packet header decoding and packet routing will significantly enhance the network switching capability of telecommunications networks. High-bandwidth secure networks will strongly enhance the military strength in remote battlefield scenarios.

Increased program funding is required in the area of developing semiconductor structures that possess advantageous nonlinear properties and ease of integration. For example, coupled quantum well structures and multiple quantum dot structures can be envisioned for such applications.

WORLDWIDE TECHNOLOGY ASSESSMENT

Canada	●●●	China	●	France	●●	Germany	●●
Israel	●●●●	Italy	●	Japan	●●●	Norway	●
Russia	●●	Sweden	●●●	Taiwan	●	UK	●
United States	●●●●						

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

In the United States many companies in the telecom industry are spending significant resources in this area. In Japan, NTT and most of the large electronics firms such as NEC, Fujitsu, Hitachi, etc., are also doing a lot of research in this area.In Europe, consortiums have been formed between several companies and universities to develop such technologies into working products. Countries involved are UK, France, Belgium, Germany, Sweden, etc.

DATA SHEET III-11.5. OPTICAL NETWORKS AND SELF-ORGANIZING SYSTEMS

Developing Critical Technology Parameter	Optical networks and self-organizing systems require nonlinear optical materials, very large NLO coefficients, and high efficiency at specific laser wavelength.
Critical Materials	Nonlinear materials. There is a need to develop materials with an increase in the nonlinear optical coefficient by a factor of 10 to 1,000 in order to reduce the required power densities to average values of a few milliwatts for a single nonlinear optical operation. Higher order nonlinearities ($n > 3$) would be highly desirable.
Unique Test, Production, Inspection Equipment	Optical measurements on nanometer scale. Improved scanning microscope techniques will be needed to work with quantum well and light emitters involving a few molecules in order to control the uniformity of large arrays and to control optical interconnections between nanodevices.
Unique Software	Simulation software.
Technical Issues	Development of materials with large optical nonlinearities at low power densities. To perform logic operations, switching should occur with pulse energies of picojoules. This limits the peak powers which can be used, and therefore requires large nonlinearities. The exact numbers depend on the geometry, the wavelength, and the pulse lengths and repetition rates. Switching with gain. Current optically driven optical switches have loss and variable time delays. For optical logic, gain is required in order to satisfy the fan-in and fan-out requirements. Additionally, timing for the pulses needs to be synchronized or restored as the pulses propagate through the circuit. Current optical amplifiers have relatively long relaxation time constants and turn on RC time constants. There is a need for switches with gain that can operate on a sub-picosecond timescale. Unilateral Devices. Most of the present optical devices are two-terminal, and it is difficult to isolate the input from the output. An all-optical three-terminal device would make optical circuit design much easier. Optical Memory. The methods for storing optical information without converging to electronics need to be reduced in the space required to store a given set of bits for variable time lengths. Additionally, the access into and out of these memories needs to be improved. Photon confinement, guiding, coupling. It would be highly desirable if simpler methods for confining optical beams to small regions of a surface were available to be compatible with submicron electronic circuits. Additionally, simple methods are needed for coupling into and out of optical circuits. Rules for interconnections in self-organizing optical systems and their implementation. As the complexity of the level of organization becomes large, it becomes impossible to write centralized control software which is reliable. Thus, when manufacturing either very large numbers of devices or in organizing them, it is necessary to define rules for the system of devices to organize themselves. Fundamental rules need to be formulated for self-organizing systems as one progresses from the elementary device toward higher levels of organization to the applications.

Major Commercial Applications	Display systems. Routers, address resolution. The Internet (self-organizing systems). It is impossible to write a centralized control for all of the websites on the Internet and the communication links tying them together as fast as changes are made. Thus, the rules must be defined that allow the nodes to control the routing between the nodes and to locate addresses which are self-organizing.
Affordability	Undetermined at this time.

RATIONALE

The military will benefit strongly from the implementation of systems incorporating self-organizing optical systems and optical display systems. A network of computers interconnected via a parallel optical bus would run military software codes specifically written for parallel computing applications such as target recognition, missile course intercept calculations, and other remote targeting applications. Automatic optical packet header decoding and packet routing will significantly enhance the network-switching capability of telecommunications networks. High-bandwidth secure networks will strongly enhance the military strength in remote battlefield scenarios.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●	China	●	Japan	●●●	South Korea	●
United States	●●						

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Japan and the United States currently lead the world in this technology.

DATA SHEET III-11.5. DIGITAL OPTOELECTRONIC SYSTEMS

Developing Critical Technology Parameter	Exploiting precise temporal control in the overall systems design to optimize photonic switching. Signal quality restoration distributed over the system. Designing systems on the basis of optoelectronic component interaction and inter-connection. Minimizing system impact of electronic/optical conversion.
Critical Materials	Complete set of optoelectronic devices for closed circuit switching systems. Compatible material systems for optoelectronic integration. Using the same format for controlling and controlled signals or very inexpensive format converters. Low power per device for complex systems.
Unique Test, Production, Inspection Equipment	Device dependent instrumentation. Interacts strongly with simulation software.
Unique Software	CAD tools for timing analysis and design. New algorithms are needed for determining distribution of signal quality restorers. Integrated optoelectronic layout tool are required for design and analysis of these optoelectronic systems. Detailed level timing and signal quality simulator.
Technical Issues	Latency-tolerant, high bandwidth system architecture. Low-cost, distributed signal quality restoration. Signal format matching between optical devices. Achievable integration levels. Robustness. Device coordination (cascading, synchronization, and power requirements).
Major Commercial Applications	After technology matures enough to compete with digital electronics. Telecommunications. High-speed multiprocessor computing. Most areas of application of digital electronics.
Affordability	Affordability is one of the major criteria for selecting devices and materials systems and eliminating expensive format conversion. System-level research required to determine cost savings. Precise control over signal delay is possible via optical format reducing cost and achieving high clock rates in spite of latency.

RATIONALE

The cost savings of interconnecting processing elements into systems with a fully connected network, which optics can provide, rather than with the partially connected networks, which electrically connected systems use, could be in the millions of dollars per system.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●	Canada	●	China	●	France	●●
Germany	●●	Japan	●●●	Norway	●	Russia	●●
Taiwan	●	UK	●	United States	●●●		

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The United States and Japan lead in this technology, but several industrialized countries have important programs underway. There is high commercial motivation.

DATA SHEET III-11.5. CHIP-DNA SEQUENCING VIA NANOMETER HOLES IN SEMICONDUCTORS

Developing Critical Technology Parameter	Fabrication of nanometer-scale holes in semiconductors surrounded by charge sensors. Understanding DNA dynamics well enough to design an operational chip within fabrication constraints.
Critical Materials	None beyond state-of-the-art semiconductor fabrication materials and processes.
Unique Test, Production, Inspection Equipment	In situ monitoring of pore size during fabrication.
Unique Software	Computer simulation of DNA dynamics at the atomic scale in an ionic solution flowing through a semiconductor pore/hole.
Technical Issues	Controlled nanometer-scale holes in semiconductors have not been demonstrated, although holes of the right size have been fabricated. Embedded FETs or other charge sensors sufficiently small have not been demonstrated, although the state of the art is not too far away.
Major Commercial Applications	Rapid, unambiguous identification of individuals from microscopic biological samples. Rapid identification of an individual's inherited allergies and susceptibilities to a wide range of diseases, allowing preventive countermeasures (e.g., frequent sensitive tests for cancers and diets/medicines to avoid Alzheimer's disease). Detection of microscopic biological pathogens in the environment.
Affordability	Potentially a compact, largely electronic module no more complex than many current measuring instruments in a clinic.

RATIONALE

The genetic code of biological agents is the determinant of infectivity of the agent and identifies those gene products in the infectious organism responsible for pathogenicity. Knowledge of the code for the agent allows development of therapeutics and prediction of the methods by which each agent can be weaponized and disseminated. (See also Part III, Section 4, pp. 15 and 16.)

WORLDWIDE TECHNOLOGY ASSESSMENT

France ●● United States ●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The only known work in this technology is in the United States and in France.

DATA SHEET III-11.5. WDM MICROCAVITY WAVEGUIDES

Developing Critical Technology Parameter	Submillimeter-scale optical WDM passive and active components. Deeper penetration of waveguide optical components into high-performance computer and communication systems.
Critical Materials	3–D fabrication of complex wageguide structures. Thin (70-nm) layers of electro-optical material.
Unique Test, Production, Inspection Equipment	Expensive, but available in optoelectronic research labs.
Unique Software	Maxwell equation solvers for large volumes in space and time to optimize design.
Technical Issues	Achieving high-Q cavities in production quantities. Integration of active control.
Major Commercial Applications	Set-top boxes for fiber high-bandwidth connections directly to residential end users. Backplanes for high-performance computing and communications switching.
Affordability	Potentially less expensive and smaller than any other option. May be no other way at any cost to reach the highest bandwidths.

RATIONALE

Compact, high-performance data processing with optical interfaces is required to achieve higher radiation-hardened space electronics and for micro-optical chip designs. These will have a significant impact on military applications ranging from lighter weight field electronics for the soldier to higher survivability for space applications to WDM optical switching systems. A civil application of WDM is in the optical switching area.

WORLDWIDE TECHNOLOGY ASSESSMENT

Israel ● Japan ●● Sweden ● United States ●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The United States and Japan have the largest programs; the Japanese motivation is mainly commercial. Israel and Sweden also have military interest.

DATA SHEET III-11.5. ULTRA-HIGH-SPEED PHOTONICS FOR NETWORKING, INSTRUMENTATION, AND SIGNAL PROCESSING

Developing Critical Technology Parameter	This area of device and systems technology focuses on advancing the state of the art in available devices, components, and systems for ultra-high-bandwidth information based technologies and applications. The critical technology parameter in these general areas are (1) bandwidth, (2) signal-processing speed (e.g., sampling speed and resolvable bits in analog-to-digital converters), and (3) agility and flexibility of device technology platforms.
Critical Materials	The critical materials most generally employed in these technology areas are primarily active semiconductor media (semiconductor lasers, photoreceivers, electro-absorbtion modulators), electro-optic media (lithium niobiate, organic polymers), and glass (for waveguides, fibers, diffractive optical components, etc.).
Unique Test, Production, Inspection Equipment	Unique test equipment may be found in developing the next generation optical function generators for testing networks and signal-processing functionality. Particularly important test equipment is the "arbitrary optical waveform generator," which is the optical analog to the conventional electrical waveform generator. This will allow system designers to generate arbitrary optical waveforms to test critical operational characteristics.
Unique Software	Critical software is mandatory to capture and process data at real-time rates of 1,000's of Gb/sec. This issue has always been the bottleneck of high-speed networking and signal-processing management. For example, high-speed optoelectronic technology has been in existence for many years; however, its incorporation into networking has been hampered by the slower development of software to manage the technology.
Technical Issues	Two technical issues that influence this technology are cost-effective packaging capabilities and minimizing insertion loss. Other technical issues may lie in the relatively large investments necessary to develop the infrastructure to allow timely development of the technology. Further development of this technology may be required for military development (e.g., radiation-hardened materials, robust operation over temperature ranges that exceed that required for telecommunication environments, and immunity to vibration and shock for mobile platform deployment may be required). Note that the use of this technology by personnel with technical training is not required.
Major Commercial Applications	Telecommunications, high-resolution analog-to-digital converters, and optical sampling oscilloscopes (all applications related to optical networking, instrumentation, and signal processing).
Affordability	A 2-in. wafer could potentially produce 50,000 devices. With the cost of a wafer being ~$5,000, the typical device cost could be as little as 10 cents. We have shown that we could build functional 100 Gb/s for all optical networks based on SOA devices.

RATIONALE

The technology described in this assessment will provide increased superiority in military and commercial applications that require high-bandwidth information links and signal processing. As the military battlefield evolves into the "digital battlefield," high-bandwidth optical links with bandwidths exceeding 100 GHz will be required. Moreover, as we continue to evolve the digital battlefield into the "remote or virtual battlefield," information-based technologies will be the primary enabling technology. Clearly, to realize the remote/virtual battlefield, the bandwidth requirements will easily exceed many terahertz, thus mandating the developing of robust, cost-effective, high-speed optoelectronic devices, components, and systems.

Specific Device/Technology Platform

Hybrid WDM–TDM Technology: This technology allows state-of-the-art information transmission and processing speeds *without* relying on a completely WDM or TDM technology platform.

Ultra-high-Resolution Photonic Analog-to-Digital Converter (PACT)

This technology will allow the quantization and digitization of analog RF signals with carrier frequencies extending to 50 GHz, relying primarily on low bandwidth electronics operating at 1 GHz.

RF Lightwave Integrated Circuits (RFLIC)

The development of the arbitrary optical waveform generator will allow for the synthesis of analog optical signals with over 100 GHz of analog bandwidth. In addition, this technology does not require ultra-high-bandwidth modulators with low operating voltages.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●	France	●●	Germany	●●	Israel	●
Italy	●●	Japan	●●●	Russia	●●	South Korea	●
Taiwan	●	UK	●●●	United States	●●●		

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

There is broad interest and activity among the industrialized nations because of the extensive commercial and military applications of broadband technology.

DATA SHEET III-11.5. OPTOELECTRONIC MICRO NETWORK TECHNOLOGY

Developing Critical Technology Parameters	Dense (Gb/sec/10 mm sq.), low power (<50 mW/Gb/sec) optoelectronic transceivers and associated micro network (passive optical interconnect fabric polymer waveguide distribution circuits) which will cost effectively ($10/Gbps).
Critical Materials	Deuterated and perflourinated polymer material. Indium phosphide.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Technical Issues	New class of batch-fabricated laser, the VCSEL. This laser eliminates need for driver chip, monitor detector, and control loop as a result of milliamp thresholds; it also eliminates need for expensive lenses and alignment procedures due to mode profile compatibility with fiber. Breakthrough in deuterated and perfluorinated polymer material with loss <10 dB/100 m and 3 GHz/100 m bandwidths, and flat loss to 1.3 µm wavelengths.
Commercial Applications	Civil networks will benefit from improved data handling through multiwave transmission in single optical fibers, enhanced network security, and greater internetwork operability.
Affordability	Successful development of deuterated and perfluorinated polymer material promises to drastically reduce costs because of the availability of very low cost connectors (relative to glass fiber connectors), which dominated costs on military platforms under $100 M.

RATIONALE

The goal of the DARPA Broadband Information Technology (BIT) thrust is to develop the advanced optical network technologies, architectures, and protocols to utilize the 30-THz bandwidth of optical fibers. This thrust will develop and demonstrate key enabling technologies for terabit optical fiber networks with global reach and capable of meeting critical DoD needs.

Optical network technology offers characteristics that satisfy many DoD requirements. These characteristics include improved data handling through multiwave transmission in single optical fibers; enhanced network security; greater internetwork operability; and reduction in hardware replacement costs through use of reconfigurable, transparent, interoperable, and cost-effective modular system components.

The BIT thrust focuses on the development and the manufacturability of integrated optoelectronic components capable of multiple-channel transmission at over 100 Gb/sec per fiber. This thrust pushes indium phosphide technology, potentially enabling the packaging of transmitter, receiver, and all ancillary components on a single chip. The technology impact resulting from the BIT programs is expected to be comparable with the impact of high-speed VLSI silicon integrated circuits on communications systems.

The goal for optoelectronic micro network technology is to replace copper cabling as interconnects to the 1-m scale in future military platforms. This is expected to achieve a 3 order-of-magnitude reduction in the cost*power* footprint) metric over current devices and greater than 2 orders of magnitude over projected commercial estimates by year 1999.

Military Applications

Military applications include enabling digitized sensor signals [radar, electronic intelligence (ELINT), electronic warfare (EW)] to be processed [e.g., space-time adaptive processing (STAP)]; SAR on-board platforms in real time rather than on the ground, eliminating remote processing/transmission delays (1.5 hrs. for F/A–18R);

reducing threat from low radar cross-section targets, enhancing resolution and potential cost savings of greater than $1 billion, by means of:

- reduction in required resources by allowing shared access to all resources (through 50× signal BW*density improvement); *and*
- effective use of A/D converters near the radar aperture allowing distributed sensor architectures that facilitate 85-percent reduction in the number of boards, thus enabling STAP on-board combat aircraft.

WORLDWIDE TECHNOLOGY

Canada	●●	Germany	●●●	Italy	●●●	Japan	●●●●
Sweden	●●	Switzerland	●●	UK	●●●	United States	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The European Union supports significant research in optoelectronics. At a Conference taking place in Bonn, August 1997, ministers of 29 European countries agreed on a number of key principles that will pave the way for a rapid growth in Europe of the use of Global Information Networks. The emergence of Global Information Networks will have a profoundly positive impact on the industry and citizens. Cross-border trade and services will be boosted as never before.

The significant but high-risk investments in technology, services, and infrastructure will be taken care of by industry and will be market led. Entrepreneurship is the crucial factor and will lead to new industrial structures either from "scratch" or through rearrangements of current businesses. Entrepreneurs and industrialists need an appropriate business environment because of the risks involved. Governments are responsible for creating this environment. Global Information Networks furthermore need a global regulatory framework that provides maximum opportunities and freedom for industry.[2]

Japan and United States have significant cooperative programs and extensive R&D.

BACKGROUND

Center of Technical Developments

The Defense Advanced Research Projects Agency, MTO

Significant Research Centers

University of Colorado, Optoelectronic Computing Systems Center. Jneff@colorado.edu

University of Arizona and University of Maryland. http:www.best.com/~worktree/f/56/202f.htm

Optoelectronics Group, Cavendish Laboratory, University of Cambridge, UK. The group was formed in 1993, when four members of the Physics and Chemistry of Solids Group decided to operate as a separate entity, with the common study of opto-electronic properties of materials as the link between their activities. Since its formation the group has grown continuously, with the addition of university faculty and Royal Society Research Fellows doubling the senior staff of the group. pob1001@cus.cam.ac.uk

Microelectronics Research Center, Georgia Institute of Technology. http://www.ece.gatech.edu/research/labs/iorg/Abstracts/ThruWaferJLT.html

Canada NRC, Photonics Systems Group

Sweden, Micro Interconnect Research Center (MIRC)

Belgium. http://www.elis.rug.ac.be/~jvc/oiic/rationale.htm

National Microelectronics Center of Ireland (NMRI). http://www.nmrc.ucc.ie/groups/AMT/optoRes.html

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2 http://www2.echo.lu/bonn/industry.html

Stanford University, Optical Interconnect Research, Prof. David A.B. Miller, http://www-snf.stanford.edu/cis/research

Major Producers/Developers

- The Cost-Effective Embedding of High-Performance Optical Interconnects (ChEEtahO) team is led by Honeywell, with membership consisting of 3M, Sun Microsystems, IBM, Cabletron, Mercury Computer, Cray Research, Boeing, Lockheed, Computing Devices International, and Northrop Grumman.
- Optical Link to Radar Digital Processor Focused Research, Inc. (FR) will design, develop, and deliver 10 functional 10-Gb/sec multimode fiber serial transmitters and receivers designed to operate over a wide temperature range at a low cost for military applications.
- The Plastic and VCSEL Network (PAVNET) team is lead by Packard-Hughes, with members consisting of Boeing, Boston Optical Fiber (BOF), Honeywell, and Lucent Technologies.
- The Parallel Optical Network Interconnect (PONI) team is led by Hewlett-Packard (HP), with membership consisting of Harris, McDonnell-Douglas Aerospace (MDA), Mercury Computer, SDL, USC, and BOF.

BACKGROUND

DARPA Program Managers

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Expert Opinions

Photonics in Telecommunications

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Paul Lagasse received a Master's degree in electrical engineering in 1969 and a Ph.D. degree in 1972, both from the University of Ghent, Belgium. In 1981 he became professor of electrical engineering at the University of Ghent, where he is now head of the Department of Information Technology (INTEC). In 1985 he also became Director of the INTEC-Division of the Interuniversity Microelectronics Centre (IMEC) in Leuven, and since 1993 he has been Secretary-General of the International Union of Radio Science (URSI). After originally working in the area of surface acoustic waves, he is now mainly active in the fields of optoelectronics, high-frequency technology, and broadband telecommunications. He is member of the board of the Flemish Institute for Science and Technology, corresponding member of the Belgian Royal Academy of Science, President of the Scientific Committee of the Royal Observatory of Belgium, and since 1997 member of the Board of Governors of IEEE Lasers and Electro-Optics Society (IEEE-LEOS).

Abstract: Over the last 20 years, photonic technology has resulted in important paradigm shifts in telecommunications. The fact that the semiconductor laser and the optical fibre were invented in the dawn of the digital age has had an important synergistic effect. The cost of transmitting information over a given distance-bandwidth product has since decreased exponentially. Currently, photonic technology for telecommunications is facing two new important challenges. First, will cost-effective photonic solutions be developed and produced, allowing to bring the fibre over that last mile to the customer? Secondly, will photonic technology provide competitive solutions for signal-processing functions such as switches that have so far been the monopoly of silicon? These challenges come at a time when regulatory, market, and technological changes are making the evolution of telecommunications impossible to predict, and when investment in long-term research is dwindling, making correct strategic research choices even more crucial.

Photonics in Recording and Displays, Professor G. Brown

email: robert.brown@sharp.co.uk

Robert G.W. Brown graduated in Physics from London University in 1973. Most of his research career has been spent at the Royal Signals and Radar Establishment in Malvern, UK, the UK Government's Electronics and Radar Research Centre. There he researched photon correlation techniques and their applications to measurement of velocity and macromolecular supensions, specialising in the use of new opto-electronic technologies.

In 1990, he was appointed Head of Opto-Electronics Research at the newly formed Sharp Laboratories of Europe in Oxford, a European Research Centre for the Japanese company Sharp Corporation. Since then, the laboratory has grown substantially, now exceeding 60 scientists and engineers, with strong activities in semiconductor opto-electronics and displays.

Professor Brown is a Fellow of the Institute of Physics, a Fellow of the Institute of Electrical Engineers, and a Special Professor in the Department of Electrical and Electronic Engineering at Nottingham University. Recently, he co-authored "A History of Optics and Opto-electronics in the Twentieth Century," published in *Twentieth Century Physics,* by IOPP and AIP, 1995.

Abstract: Our daily lives are influenced by opto-electronics to a remarkable extent. Two opto-electronic systems are now familiar to everybody—CD (compact disc) optical data storage and flat-panel displays using liquid crystal devices. Over 100 million CD systems and over 1 billion CDs are sold each year. The LCD market is many billion dollars annually. In the field of optical data storage, research and development currently includes new laser sources, new recording materials, read/write/erase capabilities, compact optics, super-resolution, and electronic data formats. In the field of flat-panel displays, liquid crystal screens are getting brighter, faster, and larger in size, but they have limits. How are those limits going to be exceeded? Will technologies such as plasma displays, organic electroluminescence, and field-emission prove competitive? What else do we want from displays?

This lecture will look briefly at the physics and technology of existing systems and then move on to describe research and development activities in progress to create future devices and systems. Key limitations and competitive ideas will form the focus for presentation and discussion.

Photonics in Interconnects for Digital Information Processing

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David Miller received a B.Sc. in Physics from St. Andrews University and a Ph.D. degree in 1979 from Heriot-Watt University, where he continued as a Lecturer from 1980 to 1981. From 1981 to 1996, he worked at Bell Laboratories, since 1987 as a Department Head. He is currently a Professor of Electrical Engineering at Stanford University. His research interests include quantum-well optics and optoelectronics and fundamentals and applications of optics in switching, interconnection, and computing systems, including “smart pixel” technologies. He has published over 180 technical papers and holds more than 30 patents. He is a Fellow of the Royal Society of London, IEEE, OSA, and APS, and was President of the IEEE Lasers and Electro-Optics Society in 1995. He was awarded the 1986 Adolph Lomb Medal of the OSA, was co-recipient of the 1988 R.W. Wood Medal, and received the 1991 Prize of the International Commission.

Abstract: As silicon electronic technology advances to larger numbers of faster devices, and as applications require more, higher speed connections to supply high-bandwidth information, demands on interconnection technology grow. The ability of electrical wires to carry digital information, however, does not scale to keep up with these capabilities and demands. The problems for wires are relatively basic, coming from the underlying physics. Optics, by contrast, can avoid many of the physical limits and problems of electrical connections. Long, thin, high-speed interconnections work well with optical fiber. Problems of, for example, impedance matching, pulse distortion, loss at high frequencies, voltage isolation, and high-frequency cross-talk can largely be avoided with optical interconnections. Optics can fundamentally reduce power for interconnections, can offer the radical solution of “free-space” connections for thousands of parallel channels and global interconnect topologies, and can solve clock-and signal-timing problems. Recent years have seen many exciting developments in the necessary optical and optoelectronic technologies, including, for example, the demonstration of greater than 4,000 high-speed optical interconnections directly into and out of a conventional silicon chip. The combination of optics, optoelectronics, and electronics offers opportunities not available from any one technology, and may allow machines to advance to the very high capacities required, for example, for future multiprocessors and telecommunications switching. The use of optics for interconnection may become crucial in providing the information-processing performance required in the next decades.

DATA SHEET III-11.5. MOEMS MANUFACTURING TECHNOLOGY

Developing Critical Technology Parameters	Develop technologies for efficient manufacturing. Specific parameters will be developed during the program.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Technical Issues	Adapt computer-aided design tools to model optical systems. Use the innate sensing and actuating capabilities of MOEMS systems to automate on-chip assembly alignment and calibration.
Commercial Applications	Telecommunications, imaging, medicine, entertainment, and information technology applications.
Affordability	This is an affordability issue because the program should provide lower cost devices for DoD systems. The program is intended to provide an infrastructure for the eventual mass production of MOEMS at low cost.

RATIONALE

The goal of this program is to develop technologies for efficient manufacturing of MOEMS. MOEMS will have many uses in generating, modulating, guiding, amplifying, and detecting optical radiation. This program is designed to help position U.S. industry to dominate the emerging market for these products in telecommunications, imaging, medicine, entertainment, and information technology.

DoD is potentially a major user of MOEMS and can benefit from improvements in manufacturing technology.

A typical military application for MOEM devices is the “fly-by-light” networks planned for military aircraft. This concept replaces copper networking with optical networks. (See also Data Sheet III-8.6—Optoelectronic Micro Network Technology.)

WORLDWIDE TECHNOLOGY ASSESSMENT

Finland	●	France	●	Germany	●	Italy	●
Japan	●	Sweden	●	UK	●	United States	●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Specific non-U.S. programs have not been identified. A number of nations may have the basic capability to launch such a program (e.g., the European Union Global Information Network initiative).

http://www2.echo.lu/bonn/industry.html

The United States industrial sponsor, in cooperation with the NIST Advanced Technology Program:

Xerox Corporation
Wilson Center for Research and Technology
800 Phillips Road
Webster, NY 14580

BACKGROUND

Program Synopsis from the NIST Web Site

The United States dominates the global market for MEMS but controls less than 10 percent of the market for photonics components. A new market now is emerging for combinations of these technologies. To provide an infrastructure for the eventual mass production of such devices at low cost, Xerox Corp., together with Maxim Integrated Products (Sunnyvale, California); Microcosm Technologies, Inc. (Raleigh, North Carolina); Optical Micro-Machines (San Diego, California); Standard Microsystems Corp. (Hauppauge, New York); and Microscan Systems, Inc. (Renton, Washington), will develop technologies for efficient manufacturing of MOEMS. Infrastructure support for this project will include the Industry-Cornell University Alliance for Electronic Packing (Ithaca, New York); Cornell Nanofabrication Facility (Ithaca, New York); the Center for Integrated Circuits and Sensors (Ann Arbor, Michigan); and Washington Technology Center (Seattle, Washington). MOEMS will have many uses in generating, modulating, guiding, amplifying, and detecting optical radiation. The consortium plans to develop a robust, low-cost process that controls the optical and other properties of devices and assembles and aligns them precisely, for multiple applications. The innate sensing and actuating capabilities of MOEMS will be used to automate on-chip assembly alignment and calibration. Computer-aided design tools will be adapted to model optical systems. The partners will use the new process to fabricate prototype MOEMS devices at Standard Microsystems Corp., a commercial foundry. This is a NIST Advanced Technology Program (ATP) that is a cooperative program with industry. The ATP project brings together a team of technology developers and end users that otherwise would not exist to tackle complex, multidisciplinary research. If successful, the project would position the United States to dominate the emerging multibillion-dollar MOEMS market and increase its share of the roughly $40 billion photonics market. The technology will have broad applications in telecommunications, imaging, medicine, entertainment, and information systems.

For project information:

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DATA SHEET III-11.5. OPTICAL WAVEGUIDES VIA CURRENT STEERING OF BEAM

Developing Critical Technology Parameter	This technology applies to monolithic integrated all-optical and optoelectronic devices. This technology will enable very high speed processing and routing of very high frequency digital optical data trains. This technology provides all-optical signal processing, “on-the-fly” decoding of packet address information, and routing of the packets to the designated destinations. Monolithic integration is key to making this technology viable for reliable error-free operation. The ultrafast semiconductor all-optical and optoelectronic switches are useful for de-multiplexing 100-Gb/sec signals in TDM applications. They can be configured to perform automatic packet address decoding and packet routing of WDM packets with latency times less than twice the duration of the packet itself. The devices can also be easily configured for parallel interconnects for local area networks and computer backplanes running at a full 64-bit data bus.
Critical Materials	High-quality semiconductor quantum-sized structures including multiple quantum wells and multiple quantum dot materials.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Not significantly different from existing software used to operate the current technology.
Technical Issues	Improvement of the energy required for switching. Issues with effects of residual-free carriers that linger on long after the switching event. Reduction in cost of fabrication and packaging.
Major Commercial Applications	Future generation of very large bandwidth optical telecommunication networks with many WDM channels operating at 100 Gb/sec. Optical backplane interconnects for local network of very high performance computers and supercomputers.
Affordability	Not identified.

RATIONALE

Monolithic integrated all-optical packet switches will be enablers for the ultimate in high-bandwidth optical telecommunications, as well as for local supercomputer networks. All-optical packet header address decoding removes a lot of the overhead penalty associated with traditional electronic packet switching.

The military will benefit strongly from the implementation of systems incorporating semiconductor all-optical switches. A network of computers interconnected via a parallel optical bus would run military software codes specifically written for parallel computing applications such as target recognition, missile course intercept calculations, and other remote targeting applications. Automatic optical packet header decoding and packet routing will significantly enhance the network switching capability of telecommunications networks. High-bandwidth secure networks will strongly enhance the military strength in remote battlefield scenarios.

Increased program funding is required in the area of developing semiconductor structures that possess advantageous nonlinear properties and ease of integration. For example, coupled quantum-well structures and multiple quantum dot structures can be envisioned for such applications.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●	Canada	●●●	China	●	France	●●●
Germany	●●●	Italy	●	Japan	●●●	Sweden	●
Switzerland	●	Taiwan	●	UK	●●●	United States	●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The United States, Germany, Canada, Japan, UK, and France have significant R&D programs. Several other nations are exploring the technology on a limited basis.